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Hazard Assessment for Usage Credits on Helicopters Using Health and Usage Monitoring System

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16. Abstract

A rotorcraft Health and Usage Monitoring System (HUMS) has two important roles. First, by accounting for maneuvers and conditions that are more severe than those that the aircraft was designed for, premature fatigue and other types of failures that could be catastrophic can be avoided. Second, by obtaining credit for service that is less demanding than those for which the aircraft was certified, longer service times can be justified, which will allow more economical operations. However, while usage monitoring has prevented failures, to date, no applicants have successfully followed the guidance of the Federal Aviation Administration Advisory Circular (AC) to develop individual aircraft usage credits. This report collects data and other information that was developed by Bell Helicopter Textron for its HUMS applications and provides it in a systematic manner to support more general and informed use of this important technology by its incorporation into the AC.

A detailed overview of the HUMS methodology is provided in this report that describes how flight condition recognition is used to determine an individual aircraft load spectrum that, in turn, is used to calculate the effective hours that correspond to this usage. The report then focuses on sources of error in usage monitoring and how these can be overcome. These include inaccurate data, missing data, and incorrect algorithms. Next, system compliance with usage applications is discussed. Finally, a prototype usage system for implementing and using HUMS is outlined, which has been evaluated for compliance with the HUMS AC. This analysis verified that the prototype system and its architecture are compliant with the intent of the AC, including required parameter rates and accuracy levels. This report provides a valuable resource for usage monitoring that can both increase safety and enhance more economical operations, while also providing the basis for the eventual linkage of HUMS with the rotorcraft damage tolerance methodology.

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LIST OF ACRONYMS

BHTI	Bell Helicopter Textron Inc.
BIT	Built-in-test
COTS	Commercial off-the-shelf
DRU	Data retrieval unit
ETS	Engine transition state
FAA	Federal Aviation Administration
FCR	Flight condition recognition
GAG	Ground-to-ground
HA	Hazard assessment
HDP	HUMS display panel
HIRF	High-intensity radiated field
HPU	HUMS processing unit
HUMS	Health and Usage Monitoring System
LLDC	Low level DC
NASA	National Aeronautics and Space Administration
OAT	outside air temperature
PAC	Power assurance check
PC	Personal Computer
POT	Potentiometer
RIN	Retirement index number
RSS	Root sum squared
RT&B	Rotorcraft Track and Balance
V_{ac}	never exceed velocity
V_h	Maximum horizontal velocity

EXECUTIVE SUMMARY

A rotorcraft Health and Usage Monitoring System (HUMS) has two important roles. First, by accounting for maneuvers and conditions that are more severe than those that the aircraft was designed for, premature fatigue and other types of failures that could be catastrophic can be avoided. Second, by obtaining credit for service that is less demanding than those for which the aircraft was certified, longer service times can be justified, which will allow more economical operations. However, while usage monitoring has prevented failures, to date, no applicants have successfully followed the guidance of the Federal Aviation Administration Advisory Circular (AC) to develop individual aircraft usage credits. This report collects data and other information that was developed by Bell Helicopter Textron for its HUMS applications and provides it in a systematic manner to support more general and informed use of this important technology by its incorporation into the AC.

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1. INTRODUCTION AND OVERVIEW.

A rotorcraft Health and Usage Monitoring System (HUMS) has two important roles. First, by accounting for maneuvers and conditions that are more severe than those that the aircraft was designed for, premature fatigue and other types of failures that could be catastrophic can be avoided. Second, by obtaining credit for service that is less demanding than those for which the aircraft was certified, longer service times can be justified, which will allow more economical operations. However, while usage monitoring has prevented failures, to date, no applicants have successfully followed the guidance of the Federal Aviation Administration (FAA) Advisory Circular to develop individual aircraft usage credits.

A previous study, funded by the FAA, NASA, and the U.S. Army Research laboratory, was conducted to assess the benefits of rotorcraft usage monitoring [1]. A separate report gives the operator's perspective [2]. Other works providing background in this area have also been published including a recent paper at the 52nd American Helicopter Society Forum titled "Usage and Structural Life Monitoring with HUMS." They adequately document the philosophy and rational that provide the basis of a Health and Usage Monitoring System (HUMS).

This document presents an end-to-end hazard assessment (HA) prepared in accordance with reference 3 for the Bell Model 412 helicopter HUMS kit. The HA begins in section 1 with an overview of the system that is proposed to be installed on the M412 helicopter, and then details the fault tree analysis of the overall system, focusing primarily on the areas where certification credit is desired. Sections 2, 3, and 4 identify and discuss the contributing areas to overall system failure, including inaccurate data, missing data, and wrong algorithms. Section 5 summarizes the proposed alternate means of computing flight hours and retirement index number (RIN) for purposes of the airworthiness part life limitations in Chapter 4 of the 412 Maintenance Manual. The emphasis is placed on describing how the mitigating factors will be incorporated into the production system. Finally, section 6 reviews usage system software considerations and allocates the software level.

1.1 SYSTEM OVERVIEW.

A basic assumption in this report is that the HUMS will be installed as an optional system that is not required for the operation of the aircraft. Vibration diagnostics and engine monitoring will be available but only as a nonrequired enhancement to the current approved maintenance practices.

The functions that are generally performed by a HUMS fall into the following four categories.

- Usage: Determine the incremental amount of component life used
- Onboard Maintenance: Rotorcraft track and balance (RT&B)
- Pilot Assistance: Logbook data and power assurance check (PAC)
- Condition Monitoring (Health): Vibration diagnostics, exceedances, and structural overloads

The data acquisition and processing system to perform these functions is presented schematically in figure 1-1. Certification credit is currently being sought only for that portion of this system that is related to usage as shown in the figure.

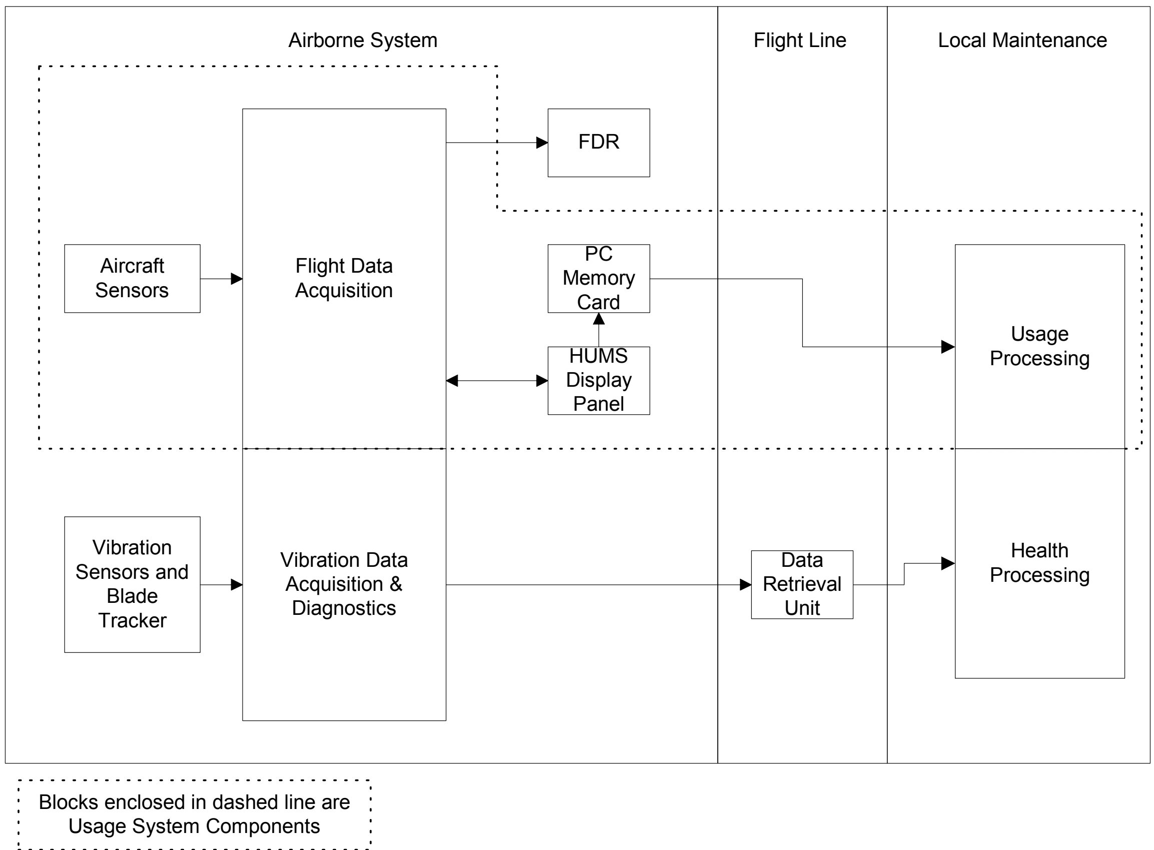

FIGURE 1-1. HUMS BLOCK DIAGRAM

1.1.1 Airborne System Description.

The basic airborne system for usage monitoring generally comprises the following types of equipment.

1. The HUMS processing unit (HPU). The HPU is a centralized data acquisition and processing unit that acquires data; converts analog, digital bus, and discrete inputs into digital form; preprocesses the data; provides display output to the HUMS display panel (HDP); provides continuous usage parameter data to a personal computer (PC) memory card interface for storage; and provides access to the data for a piece of ground support equipment called the data retrieval unit (DRU). The HPU performs a continuous built-in-test (BIT) on the system elements.

2. A set of sensors and transducers. These provide signals to the HPU through wiring harnesses. Many signals are provided to the HPU by connection to existing aircraft systems via harnesses added to the aircraft.

3. The HUMS Display Panel. The HDP is mounted in the cockpit and displays operational information to the pilots. Internal to the HDP are two PCMCIA type II card slots. These card slots will accommodate FLASH memory cards, used to store continuous usage parameter data. The HDP will contain a BIT and will send the results to the HPU.

1.1.2 Ground Station Description.

The ground station for a usage monitoring system generally consists of a commercial off-the-shelf (COTS) PC with a tape backup system, a PCMCIA card slot, and a printer.

Minimum system requirements will be published in the Configuration Index Document for the project. The only software being developed specifically for this project is the usage software. COTS support software will be used as discussed in section 7.

1.2 USAGE MONITORING OVERVIEW.

This section presents an overview of the system to be used to determine the fatigue life usage for dynamic components. A list of the possible parts to be tracked by usage monitoring is given in table 1-1, which is derived from Bell Helicopter's 412EP Maintenance Manual, Chapter 4. The actual parts for which usage monitoring will be performed will be a subset of the list given in the maintenance manual. Three different types of damage, and the basis by which usage monitoring will be used to determine the effects of damage on the listed parts, are:

- Spectrum damage—based on actual aircraft spectrum
- Ground-air-ground (GAG) loading damage—based on RIN accumulation
- Internal hoist operations—based on number of operations using the internal hoist in the right forward position

These three types of damage are described in more detail in the following sections. Note that while all the parts included in table 1-1 are affected by spectrum damage, a few are also subjected to damage from GAG loading and hoist operations. These parts are delineated in table 1-1.

1.2.1 Spectrum Damage.

Usage parameter data can be used to determine the time in each maneuver category (spectrum) for each HUMS-equipped aircraft. This spectrum will be combined with existing fatigue strength and load level survey certification data to determine the amount of service life that has been expended on fatigue critical parts. Figure 1-2 presents a diagram of this methodology.

TABLE 1-1. COMPONENTS THAT CAN BE TRACKED WITH A USAGE SYSTEM

Part Nomenclature	Part Number	Airworthiness House
Yoke Assembly	412-010-101-123	5,000 hrs [(1)]
Spindle Assembly	412-010-156-105	5,000 hrs
Spindle Assembly	412-010-156-113	10,000 hrs
Spindle Assembly	412-010-190-101	5,000 hrs
Pitch Horn Assembly	412-010-149-105	5,000 hrs
Pitch Horn Assembly	412-010-149-111	10,000 hrs
Retention Bolt	412-010-124-105	5,000 hrs
Retention Bolt (Expandable)	412-010-137-103	5,000 hrs
Damper Bridge	412-010-104-101	5,000 hrs
Damper Bridge	412-010-185-101	10,000 hrs
Damper Bridge	412-010-185-109	15,000 hrs
Damper Bridge	412-010-183-101	10,000 hrs
Damper Bridge	412-010-183-109	15,000 hrs
Damper Bridge	412-018-068-101	10,000 hrs/15 yr
Damper Bridge	412-010-170-101	10,000 hrs/15 yr
Fitting	412-010-111-101	5,000 hrs
Bracket Assembly, Pendulum Absorber	412-010-214-101	10,000 hrs
Bracket Assembly, Pendulum Absorber	412-010-215-101	10,000 hrs
Bracket Assembly, Pendulum Absorber	412-010-264-101	10,000 hrs
Arm Assembly, Pendulum Absorber	412-010-217-101	5,000 hrs
Arm Assembly, Pendulum Absorber	412-010-263-101	5,000 hrs
Pitch Link Tube	412-010-425-113	5,000 hrs
Pitch Link Bearing Assembly	412-010-182-101	5,000 hrs
Pitch Link Rod End Bearing	412-010-412-101	5,000 hrs
Pitch Link Rod End Bearing	412-010-438-101	5,000 hrs
Pitch Link Rod End Bearing	412-010-400-101	5,000 hrs
Swash Plate Link Rod End Bearing	412-010-412-101	5,000 hrs
Swash Plate Link Rod End Bearing	412-010-448-101	5,000 hrs
Swash Plate Link Rod End Bearing	412-010-400-103	5,000 hrs
Swash Plate Link Tube	412-010-406-105	5,000 hrs
Drive Hub Assembly	412-010-445-101	10,000 hrs
Rephrasing Lever Assembly	412-010-403-109	1,250 hrs
Rephrasing Lever Assembly	412-010-403-113	5,000 hrs
Drive Link Assembly	412-010-405-101	5,000 hrs
Drive Link Assembly	412-010-193-101	5,000 hrs
Swash Plate Outer Ring	412-010-407-105	10,000 hrs

TABLE 1-1. COMPONENTS THAT CAN BE TRACKED WITH A USAGE SYSTEM (Continued)

Part Nomenclature	Part Number	Airworthiness House
Swash Plate Support Assembly	412-010-443-101	5,000 hrs
Swash Plate Support Assembly	412-010-409-105	5,000 hrs
Swash Plate Support Assembly	412-010-453-101	5,000 hrs
Gimbal Ring	412-010-404-101	9,000 hrs
Collective Sleeve	412-010-408-003	9,000 hrs
Collective Lever Assembly	412-010-408-101	10,000 hrs
Main Rotor Mast Assembly	412-010-101-105	10,000 hrs(1) or 80,000 RIN(2)
Main Rotor Mast Assembly	412-010-101-121	10,000 hrs(1) or 80,000 RIN(2)
Cap, Retention	412-010-161-101	10,000 hrs
Cap, Retention	412-010-171-101	10,000 hrs
Cone	412-010-165-101	10,000 hrs
Cone	412-010-169-101	10,000 hrs
Drive Pin	412-010-166-101	10,000 hrs
Upper Cone Seat	412-010-164-101	10,000 hrs
Upper Cone Seat	412-010-174-101	10,000 hrs
Upper Cone Seat	412-010-186-101	10,000 hrs
Splined Plate Assembly	412-010-177-101	10,000 hrs
Splined Plate Assembly	412-010-167-105	10,000 hrs
Splined Plate Assembly	412-010-177-113	10,000 hrs(1) or 80,000 RIN(2)
Lower Cone Seat	412-010-178-101	10,000 hrs(1)
Lower Cone Seat	412-010-168-105	10,000 hrs(1)
Lower Cone Seat	412-010-056-105	10,000 hrs(1)
Cone	412-010-179-101	10,000 hrs
Adapter, Tail Rotor Drive Quill	212-040-206-103	5,000 hrs
Gear-Spiral Bevel, Tail Rotor Drive Quill	212-040-151-101	5,000 hrs
Planetary Spider	412-040-785-101	2,500 hrs
Tail Rotor Drive Adapter, Coupling	412-040-634-101	5,000 hrs
Tail Rotor Drive Adapter, Gearbox	412-040-625-101	5,000 hrs
Tail Rotor Drive Adapter, Flanged	412-040-622-101	5,000 hrs

(1) Four additional hours must be logged in for each hoist operation performed in the penalty center of gravity region (see figure 4-1 of reference 4 for a full explanation).

(2) The measure that occurs first is the one that governs.

A list of the measured onboard data parameters required for usage evaluations, together with their sources and recorded frequency rates, is presented in table 1-2. All the parameters in this list can be recorded in the aircraft on a removable memory card for postprocessing. Postprocessing will occur on the ground, using a PC and specially designed usage software. In addition to the parameters recorded in the airborne unit, a second group of parameters will be derived using measured parameters. These derived parameters are presented in table 1-3.

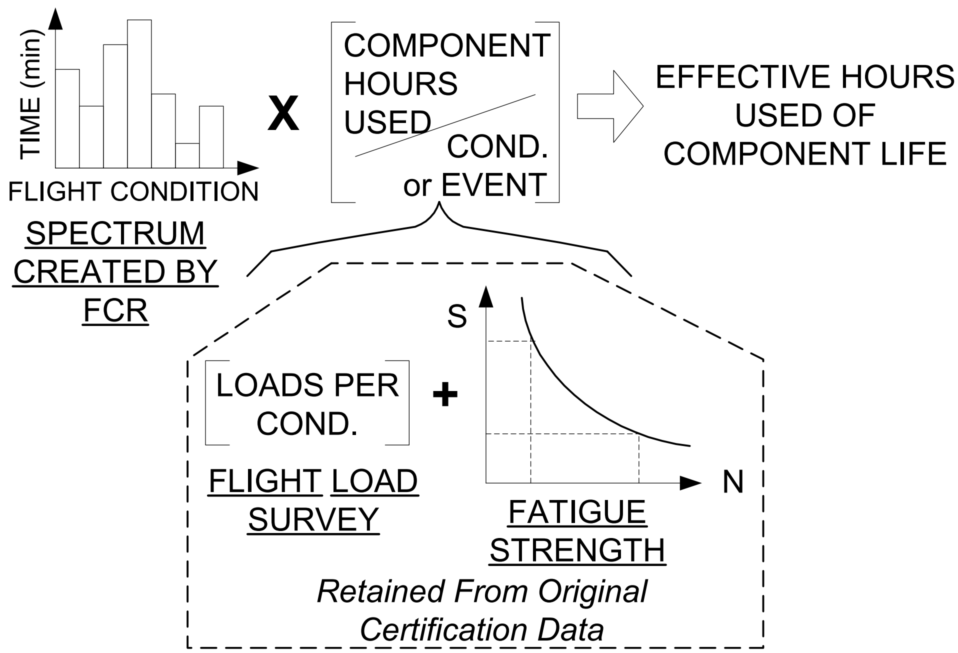

FIGURE 1-2. COMPONENT LIFE DETERMINATION PROCESS USING FLIGHT CONDITION RECOGNITION

To determine the actual operating spectrum, ground processing will use predefined algorithms to classify the flight conditions using the current values of the parameters presented in tables 1-2 and 1-3. This process is referred to as flight condition recognition (FCR). These predefined algorithms have been formulated by analyzing data recorded during scripted flight profiles flown during the load-level survey, and in other model 412 scripted flights, as available. All flight conditions performed for the aircraft certification load-level survey [5] will be recognized. These conditions are presented in table 1-4.

The FCR algorithms will be structured such that, if a condition cannot be identified, the time that the aircraft spent in that condition will be classified as unrecognized. Conservatively, the time accumulated as unrecognized will be counted towards the maneuver from the M412 load-level survey with the highest damage rate for each part. However, the time history data for all usage parameters for each instance of an unrecognized maneuver will be recorded in a unique file for subsequent analysis by Bell Helicopter Textron Inc. (BHTI). The time categories for each flight condition will be divided into three gross weight ranges, which correspond to those used in the load survey, i.e., less than 8,000 lbs, from 8,000 to 10,000 lbs, and from 10,000 to 11,900 lbs.

TABLE 1-2. PARAMETERS OBTAINED FROM AIRBORNE UNIT

No.	Parameter Name	Frequency	Source
1	Pressure Altitude	1 Hz	Air Data System (1)
2	Indicated Airspeed	1 Hz	Air Data System (1)
3	Magnetic Heading	4 Hz	Aircraft Instrument Sensor
4	Pitch Attitude	4 Hz	Aircraft Instrument Sensor
5	Roll Attitude	4 Hz	Aircraft Instrument Sensor
6	Normal Acceleration (Nz)	8 Hz	Added HUMS Sensor
7	Main Rotor rpm	2 Hz	Aircraft Instrument Sensor
8	Engine No. 1 Torque	8 Hz	Aircraft Instrument Sensor
9	Engine No. 2 Torque	8 Hz	Aircraft Instrument Sensor
10	Mast Torque (where applicable)	8 Hz	Aircraft Instrument Sensor
11	Outside Air Temperature	1 Hz	Air Data System (1)
12	Altitude Rate (vertical velocity)	4 Hz	Air Data System (1)
13	Collective Stick Position	4 Hz	Flight data recorder channel from dual-channel position sensor installed for F/A cycle stick
14	F/A Cyclic Stick Position	4 Hz	
15	Lateral Cyclic Stick Position	4 Hz	
16	Tail Rotor Pedal Position	4 Hz	
17	Time and Date	0.25 Hz	HUMS System
18	Pilot Entered Gross Weight	Once per Flight (2)	Entered at Cockpit Display Panel (3)
19	On Ground Discrete	1 Hz	HUMS System
20	Aircraft Flight Hours	1Hz	HUMS System

(1) Dedicated air data computer for HUMS. Uses same pitot/static source as in the copilot's display.

(2) Fuel burn algorithm will decrement the gross weight as the aircraft is in flight.

(3) If the pilot does not enter a value, the system defaults to the gross weight that causes the most damage for each component. The entry has to be reinitialized, or entered again, after each landing.

TABLE 1-3. PARAMETERS DERIVED IN USAGE GROUND STATION

Parameter Name	Frequency	Derivation Technique
Rate of Change Indicated Airspeed	1 Hz	d/dt (Indicated Airspeed)
Rate of Change of Magnetic Heading	4 Hz	d/dt (Magnetic Heading)
Pitch Rate	4 Hz	d/dt (Pitch Attitude)
Roll Rate	4 Hz	d/dt (Roll Attitude)
Moving Average of Rate of Climb	4 Hz	Average of four previous samples, the current sample, and the next four samples
Engine State 1. Twin 2. Single 3. Auto	4 Hz	<u>Rules When No Previous State is Available</u>: (1) Q_{E1} and Q_{E2} > 10% = Twin; (2) Q_{E1} and Q_{E2} > 5% = Auto; (3) Either Q_{E1} or Q_{E2} > 5%, but not both = Single; <u>Rules When Previous State is Available</u>: (1) Previous State = Auto a. Q_{E1} and Q_{E2} > 10% = Twin; ETS = A-> T b. Q_{E1} and Q_{E2} > 10% = Single; ETS = A-> S c. otherwise still Auto; ETS = None (2) Previous State = Single a. Q_{E1} and Q_{E2} > 10% = Twin; ETS = S-> T b. Q_{E1} and Q_{E2} > 5% = Auto; ETS = S-> A c. otherwise still Single; ETS = None (3) Previous State = Twin a. Q_{E1} and Q_{E2} > 5% = Auto; ETS = T-> A b. Q_{E1} and Q_{E2} > 5% = Single; ETS = T-> S c. otherwise still Twin; ETS = None
Engine Transition State (ETS) 1. Twin to Single: T->S 2. Twin to Auto: T->A 3. Single to Twin: S->T 4. Single to Auto: S->A 5. Auto to Twin: A->T 6. Auto to Single: A->S 7. None		
Rate of Change of Collective Stick Position	4 Hz	d/dt (Collective Stick Position)
Rate of Change of F/A Cyclic Stick Position	4 Hz	d/dt (F/A Cyclic Stick Position)
Rate of Change of Lateral Cyclic Stick Position	4 Hz	d/dt (Lateral Cyclic Stick Position)
Combined Engine Torque	4 Hz	$Q_{E1} + Q_{E2}$
Peak and Valley (Pedal)	4 Hz	True when the peak/valley cycle of the position parameter exceeds threshold within a defined time.
Peak and Valley (Longitudinal Stick Position)	4 Hz	
Peak and Valley (Lateral Stick Position)	4 Hz	

TABLE 1-4. FLIGHT CONDITIONS RECOGNIZED

Number	Flight Condition	Time or Event	FCR Module
1	Rotor Start	Event	On Ground
2	On Ground	Time	On Ground
3	Takeoff, flat surface (>3° side slope)	Event	Takeoff
4	Landing, flat surface (>3° side slope)	Event	Landing
5	Shutdown	Event	On Ground
6	Steady Hover at 314 rpm	Time	Low Airspeed
7	Steady Hover at 324 rpm	Time	Low Airspeed
8	Hover Right Turn	Time	Low Airspeed
9	Hover Left Turn	Time	Low Airspeed
10	Hover-Longitudinal Control Reversal	Time	Low Airspeed
11	Hover-Lateral Control Reversal	Time	Low Airspeed
12	Hover-Pedal Control Reversal	Time	Low Airspeed
13	Right Sideward Flight	Time	Low Airspeed
14	Left Sideward Flight	Time	Low Airspeed
15	Rearward Flight	Time	Low Airspeed
16	Normal Takeoff and Acceleration to Climb Airspeed	Time	Accel/Decel
17	Normal Approach and Landing, Twin Engine	Time	Accel/Decel
18	Normal Approach and Landing, Single Engine	Time	Accel/Decel
19	Level Flight, Twin Engine—0.4 V_h at 314 rpm	Time	Level Flight
20	Level Flight, Twin Engine—0.4 V_h at 324 rpm	Time	Level Flight
21	Level Flight, Twin Engine—0.6 V_h at 314 rpm	Time	Level Flight
22	Level Flight, Twin Engine—0.6 V_h at 324 rpm	Time	Level Flight
23	Level Flight, Twin Engine—0.8 V_h at 314 rpm	Time	Level Flight
24	Level Flight, Twin Engine—0.8 V_h at 324 rpm	Time	Level Flight
25	Level Flight, Twin Engine—0.9 V_h at 314 rpm	Time	Level Flight
26	Level Flight, Twin Engine—0.9 V_h at 324 rpm	Time	Level Flight
27	Level Flight, Twin Engine—1.0 V_h at 314 rpm	Time	Level Flight
28	Level Flight, Twin Engine—1.0 V_h at 324 rpm	Time	Level Flight
29	Level Flight, Twin Engine—Vne at 314 rpm	Time	Level Flight
30	Level Flight, Twin Engine—Vne at 324 rpm	Time	Level Flight
31	Twin-Engine Full-Power Climb	Time	Climbs/Descents
32	Single-Engine Full-Power Climb	Time	Climbs/Descents
33	Low-Speed Cyclic Pull-Up	Time	Pull-Up
34	High-Speed Cyclic Pull-Up	Time	Pull-Up
35	Normal Acceleration From Climb Airspeed to 0.9 V_h	Time	Accel/Decel
36	Low Speed Right Turn	Time	Turn

TABLE 1-4. FLIGHT CONDITIONS RECOGNIZED (Continued)

Number	Flight Condition	Time or Event	FCR Module
37	High-Speed Right Turn	Event	Turn
38	Low-Speed Left Turn	Time	Turn
39	High-Speed Left Turn	Event	Turn
40	Level Flight Longitudinal Control Reversal	Event	Level Flight
41	Level Flight Lateral Control Reversal	Event	Level Flight
42	Level Flight Pedal Control Reversal	Time	Level Flight
43	Deceleration From 0.9 V_h to Climb Airspeed	Time	Accel/Decel
44	Twin-Engine Partial Power Descent	Time	Climbs/Descents
45	Single-Engine Partial Power Descent	Time	Climbs/Descents
46	Twin-Engine-Single-Engine Transition Full-Power Climb	Event	Power Transitions
47	Twin-Engine-Single-Engine Transition Level Flight	Event	Power Transitions
48	Single-Engine-Twin-Engine Transition Partial Power Descent	Event	Power Transitions
49	Twin-Engine-Autorotation Transition at Low Speed	Event	Power Transitions
50	Twin-Engine-Autorotation Transition at High Speed	Event	Power Transitions
51	Autorotation	Time	Climbs/Descents
52	Twin-Engine Recovery From Autorotation	Event	Power Transitions
53	Autorotation Right Turn	Time	Climbs/Descents
54	Autorotation Left Turn	Time	Climbs/Descents
55	Side-Sloped Landing (≥ 3° and < 5° side slope)	Event	Landing
56	Side-Sloped Takeoff (≥ 3° and < 5° side slope)	Event	Takeoff
57	Side-Sloped Landing (≥ 3° and < 10° side slope)	Event	Landing
58	Side-Sloped Takeoff (≥ 3° and < 10° side slope)	Event	Takeoff
59	Unrecognized	Time	All Submodules

V_h = Maximum horizontal velocity
Vne = Never exceed velocity

The major benefit of usage monitoring that uses FCR is an accurate accounting of how the aircraft has been operated. This information may allow an increased time in service for components on aircraft that were operated less severely than the assumed spectrum used in certification calculations. To mitigate the effects of unanticipated maneuvers, any increase in service life shall be limited to a factor of two. Of even more importance, an increase in safety is achieved for those aircraft operated more severely than the assumed certification spectrum because their parts will be retired from service earlier than the initial certification calculation would allow.

The current recommended component retirement hours, which were established for use with actual aircraft hours, will be retained. HUMS effective hours will be determined for each component by HUMS and used in lieu of actual aircraft flight hours for the component life expended calculations. These calculations, in terms of effective hours, will replace actual aircraft hours only when the required aircraft parameter data are available and are valid.

1.2.2 Ground-Air-Ground Cycle Counting.

The components on the M412 that are most susceptible to GAG cycles are also monitored using aircraft parameter data. Damage cycles are counted and summed in a cumulative index that is referred to as the RIN. The RIN for a new part is zero. The part is retired when a predetermined maximum allowable RIN number is attained.

The RIN can be recorded manually or automatically with a torque event-monitoring algorithm. The manual method consists of counting each takeoff or external lift cycle as one RIN. For logging operations, two RIN are counted for each external lift. The automated system measures either combined engine torque or measured mast torque and applies a rain-flow algorithm to determine the torque cycles incurred by the aircraft. Torque cycles below the endurance limit threshold are truncated because they do not cause damage to the components. Damaging torque cycles are processed using BHTI's damage equation and the material constants determined by testing for the part. Incremental damage is then calculated and subsequently converted to an integer RIN value, which is used by the operator's maintenance facility for determining when GAG-effected parts should be retired.

1.2.3 Parts Affected by Hoist Operation Cycles.

Certain parts are adversely affected by operation when the internal hoist is installed in the right forward position. For these selected parts, 4 hours are logged against each part's retirement time for each hoist operation. The pilot will still be required to enter these operations manually into the logbook to account for these hours. Logbook hoist cycles will be transferred to the usage ground station by a manual entry process.

1.3 OTHER NONREQUIRED FUNCTIONS.

The following available functions are not required for usage part life credits:

- The PAC processing is performed in the HPU, and both the data used in calculations and the calculated results are displayed on the HDP.

- The vibration data are obtained from accelerometers specifically installed for HUMS. A blade tracker can also be installed when required for RT&B. The results are displayed on the RT&B page of the HDP.

- The vibration analysis, RT&B, exceedance monitoring, and trend data are processed with a separate HUMS processor card. The results are downloaded by the DRU, which can provide a quick look at the results to identify possible special inspections or needed maintenance actions.

- Data will be transported to a HUMS health monitoring ground station to store and further process data. This ground station also provides a more detailed look at the results.

These nonrequired functions have no affect on the usage system.

1.4 FAULT TREE ANALYSIS.

The fault tree presented in figure 1-3 and the analyses described in sections 2 and 3 focus on the usage monitoring aspect of the HUMS. The hazard assessment for the system installation is presented in reference 6. The fault tree presents a top down analysis of the usage monitoring system. The analysis starts with the worst-case condition, i.e., a fatigue life-limited part being left in service too long, which is considered a potential catastrophic failure condition. The analysis breaks down the potential faults that could be the cause(s) of this condition, and how each cause can be compensated for or prevented.

Incorporating usage monitoring to determine when life-limited parts should be retired will only change one aspect of the original certification process: the spectrum that is used to determine part life. Since FCR will realize the actual spectrum each aircraft is flown, it is imperative that the spectrum is determined correctly. If the spectrum is not determined correctly, a life-limited part could be left on the aircraft too long, leading to the possibility that a dynamic component could fail during flight.

The factors that can affect the correctness of the spectrum are:

- Inaccurate data
- Missing data
- Wrong algorithms

These factors, along with mitigating factors that can be used to nullify the effects of each problem, are discussed in detail in the following sections.

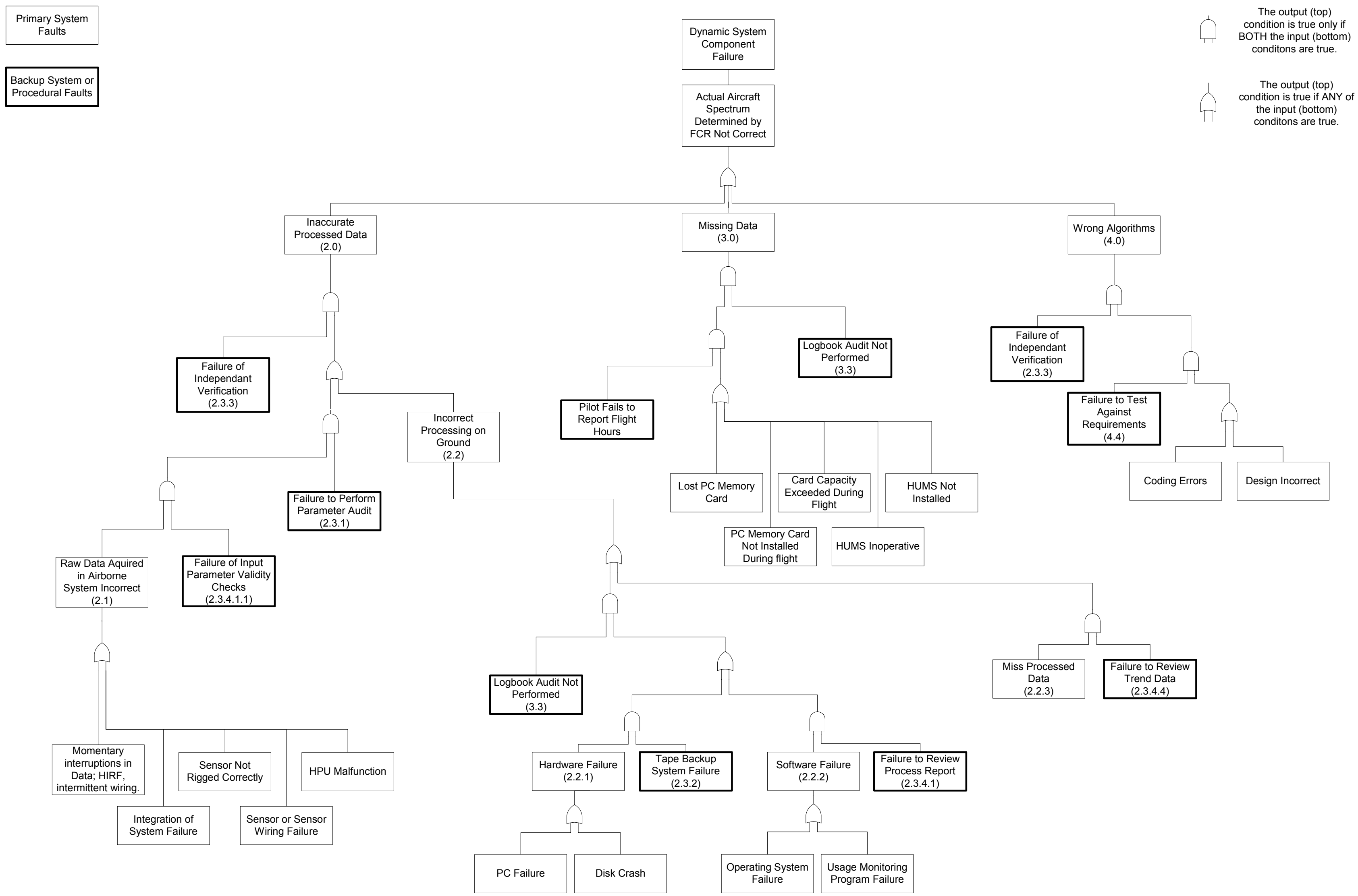

FIGURE 1-3. FAULT TREE ANALYSIS FOR HUMS USAGE CREDITS

2. INACCURATE DATA.

Inaccurate data can result from (1) the airborne system acquiring incorrect raw data or (2) the ground processing affecting the data in an adverse way. These topics are discussed in detail in this section.

2.1 INCORRECT ACQUISITION OF DATA BY THE AIRBORNE UNIT.

Basic aircraft flight data are acquired from existing onboard sensors by the flight data portion of the HPU. The sensor inputs to the HPU are analog type, except for the air data, which are an ARINC 429 input. These data are digitized, formatted, and sent to the flight data recorder (FDR) (if installed) and to a removable memory card. The data from the memory card are transferred to the usage ground computer to perform component life calculations. Errors in this path can occur from the following, all of which are detectable:

- Sensor or sensor wiring failure
- Sensor not rigged correctly
- Integration of system failure (wiring, power supply)
- HPU malfunction
- Momentary interruptions

2.1.1 Sensor or Sensor Wiring Failure.

The failure of a sensor, or of the wiring between the HPU and a sensor, can be detected by validity signals and reasonableness limits that are provided by the HPU. Checks that will invalidate the data associated with failures of this nature will be incorporated into the ground-based software. A periodic parameter audit will also detect this class of failures.

2.1.2 Sensor Rigged Incorrectly.

The maintenance manual requires that the transducers for collective, cyclic positions, and pedal positions be rerigged after the control system has been worked on. Parameter correlation checks, to be discussed in detail in section 2.3.5.3, would be used to detect misrigged transducers. Full throw control position checks after sensor maintenance will also detect a rigging problem.

2.1.3 Integration of System Failure (Wiring and Power Supply).

A failure of the HPU due to broken power wiring or to power supply problems would cause either a total shutdown of the system or the flow of data to the PC memory card to be stopped. In either case, no data would be recorded.

Because this situation would not introduce incorrect data, it is considered to be the same as a HUMS inoperative failure. These are covered in section 3. Intermittent wiring problems are addressed in the section 2.1.5.

A failure from an output of the HPU to the PC memory card unit would cause a loss of data and would also be addressed in section 3. A wiring failure from the HPU to the HDP would prevent the display from working and would be detected during a parameter audit.

2.1.4 Malfunction of the HPU.

A total failure of the HPU results in the PC memory card being devoid of parameter files. This failure is considered a HUMS inoperative failure and is covered in the section 3. A partial failure of the HPU would be detectable by BIT, by the usage software's input parameter validity checks, or by cross checks by the pilot during a parameter audit. A malfunction of the HPU that causes one or more parameters to be inaccurate (no such failure conditions are known, but this analysis assumes there may be such a condition) will be detectable by the input parameter validity checks if the inaccuracy causes the parameter to go out of range. If an inaccurate parameter remained in range, it would be detectable by the periodic parameter audit. Any data taken during a period of time where parameter data may have been inaccurate will be invalidated. Invalid data are conservatively gap filled as discussed in section 4.4. Intermittent data and misprocessed data are covered in sections 3.1-3.3.

2.1.5 Momentary Interruptions.

Momentary interruptions in the collection of data due to High Intensity Radiated Field (HIRF) or intermittent wiring will be detectable. Parameter validity checks are accomplished on the usage input data stream and these checks, along with parameter correlation, should catch intermittent problems with single parameters and will invalidate the input data for the duration of the problem. Invalid input data are conservatively gap filled.

The HIRF susceptibility of the HPU will be qualified to 5 volts/meter. Testing will be performed at levels above 5 volts/meter to quantify the effects of HIRF on the data. If the test results show that HIRF could adversely affect the data in a way that cannot be detected, then the HIRF qualification level will be revised. I-HIRF effects are typically short lived, however, and are not expected to have any significant impact other than a brief loss of data. Such losses of data will be conservatively gap filled, which is discussed elsewhere in this document.

2.2 INACCURATE DATA CAUSED BY GROUND PROCESSING.

Ground processing that corrupts accurate data obtained from the airborne unit may be the result of a software or hardware problem.

2.2.1 Hardware Failure.

Hardware faults fall into three categories:

1. Partial system failures such as disk crashes that could cause the loss of data.

2. A full total equipment failure such as a PC failure. Because data loss resulting from a disk crash can be alleviated by keeping backup copies of all data, a tape backup unit is

included in the ground station design. PC failure is recovered by replacing the PC, then reloading the data via tape backup.

3. Intermittent equipment failures or processor glitches and is covered in section 2.2.3.

2.2.2 Software Failure.

Software problems can be related to the operating system and to the usage program. Failure in the operating system can be minimized by using a robust COTS operating system. Windows NT has been selected for this purpose. However, should a fault occur, the result would be an aborted or locked up usage program. In this case, no process report would be available. However, an operator-initiated procedure requiring review of the process report (see section 2.3.5) will provide adequate opportunity to discover a failure of this nature.

Problems with the usage software will be detectable either from error messages printed in the process report or from the fact that there will be no process report at all. A failure of the software that aborts the program will result in a missing process report, and the failure can, therefore, be discovered and corrected or worked around (e.g., by data gap fill). An algorithmic failure would lead to either excessive flight hours in the unrecognized flight regime category or abnormal component usage rates would be experienced. Appropriate error messages will be in the process report for these conditions. The nature of the error detection processing is discussed in section 2.3.

Software problems will be reported to Bell Helicopter and then corrected using DO-178B guidelines for software change. The corrected software will then be provided to all usage ground station operators.

2.2.3 Misprocessed Data.

Processor glitches or other failures causing misprocessed data that surface after initial testing would likely be detectable over a period of time by reviewing the trends of the data. Periodic end-to-end testing of the usage ground station software using a known set of inputs and outputs on the PC memory card will also be used to ensure that the usage system is not misprocessing data. The subject of this ground station end-to-end testing is covered in more detail in section 2.3.3.

2.3 MITIGATING FACTORS FOR INACCURATE DATA.

Incorrect data can be detected in several ways. First, the majority of the data that the HUMS unit provides for usage are also displayed to the pilot via his instruments. Second, the HUMS system itself contains checks for out of range parameters. And, last, the software in the ground processing includes functions that can detect inaccurate data.

2.3.1 Cockpit Verification of Data Using the HUMS Display Panel.

The same data required for usage are also sent to the HUMS display panel in the cockpit where the actual sensor parameter data for usage can be viewed on a utility page. Periodically, this display is used to compare the HPU output data to the sensor data, most of which can be read on the cockpit instruments. A portion of these checks can be performed on the ground while others, such as airspeed, may need to be performed in the air. This activity is called the parameter audit.

The results of the parameter audit will be input into the usage ground station before any effective life calculations are released and used by the maintenance facility. The time interval on this audit will be flexible but is not expected to exceed 1 month. The primary motivation for the operator to accomplish this audit often is that should the audit fail, all data taken since the previous audit may have to be invalidated, and thus, the operator could loose all his usage credit for that time.

Sensor errors will be apparent to the flight crew when their instruments do not function as required during flight, since HUMS receives most of its data from the same sources as the aircraft instruments, see specification in table 1-2.

2.3.2 Tape Backup System.

A tape backup system is included in the ground station configuration to provide a way to preserve the hard drive data files against system failures. If data are lost due to a system failure or for any other reason and are not recovered, then the operator's cost-effectiveness is penalized by the requirement to conservatively gap fill all the lost data. There is a profit incentive for tape backup to be designed into the system so that the operator will make frequent (possibly even daily) tape backups to reduce the amount of data lost in system failures. The operator will establish a procedure to ensure that a tape backup of the usage data is made frequently.

To prevent the hard drive from becoming full, parameter data will be archived using the tape backup system. Parameter data will be archived after they are processed.

2.3.3 Usage System Integrity Check Using the Master Card.

A special PC memory card will be prepared that contains known good parameter data for a fictitious test aircraft. The flight regimes recorded on this Master Card and the associated incremental part damage for the test aircraft will be known and documented in a system integrity check test procedure. The Master Card will be retained at the ground station and can be used at any time to check the integrity of the usage ground station. This can be done by examining the incremental damage to the test aircraft when the card is processed. No release of test aircraft data to the maintenance facility will be allowed in order to avoid confusion.

At system setup, and at any time a change is made to the system, the usage system integrity check must be performed using the Master Card. Monthly use of the Master Card will be required to ensure that the usage ground station is functioning properly. This periodic system integrity check constitutes an independent verification of the usage system since known inputs should produce known outputs.

2.3.4 The Release Report.

There are two types of reports that are used to report the results given by the usage software. First, the Process Report documents the correct processing of each PC card. Second, the Release

Report documents the results of system audits and the release of data to the maintenance facility. The Process Report is the more complex of the two and will be discussed in section 2.3.5.

The Release Report documents the results of the usage calculations and the release of data to the maintenance facility. The operator's procedures for releasing data to the maintenance data tracking facility requires that each Release Report be reviewed. An error in the software that aborts the program will result in a missing report that can be discovered and corrected, or worked around (data gap fill) when necessary. The Release Report provides confirmation that all applicable parameter data have been validated before the release of the usage calculation results based on those parameter data.

2.3.5 The Process Report.

The Process Report documents the results from parameter data processing. It also documents the results of system error detection processing. The operator's procedure for processing the parameter data requires review of the Process Report for each PC memory card. A failure of the software that aborts the program will result in a missing Process Report, and it can, thus, be discovered and corrected. A processing error could lead to either excessive flight hours in the unrecognized flight regime category or in abnormal component usage rates when compared to previous data history. These conditions will be noted on the Process Report.

Excessive unrecognized data will be reported on the Process Report and will, thus, be detected by examination of the report. When this excess alert is reported, the operator will perform a parameter audit to make sure the data being collected are accurate. If this audit does not show any problems, then the operator will require the pilots and maintainers responsible for the aircraft to identify if any of their activities or actions may have affected the data. Possible causes could be changes in flying style, the mission, a replacement of parts, or any adjustments that have been made. If no changes are found that may have affected the data, the operator will contact Bell Product Support for assistance in resolving the occurrence of excessive unrecognized data. The normal Bell product support process will analyze the operator's data and find the cause of the abnormality.

Additional detail on this error detection processing, as well as other messages that may appear on the Process Report, are described in the following sections. While the periodic parameter audit is generally sufficient to determine the validity of the parameter data, some system functions have been added to the design in order to reduce the amount of data that are lost when a failure occurs. For example, if a sensor failure occurs one day after a monthly parameter audit that is not discovered until the next parameter audit, then a full month of data will have to be invalidated and gap filled. These added system functions are intended to detect faults and report them on the Process Report to prevent the loss of significant amounts of data.

2.3.5.1 Parameter Validity Checks.

Out of range parameters can be detected by validity bits or reasonableness limits. Table 2-1 presents a list of the reasonableness limits for the M412 Helicopter.

TABLE 2-1. REASONABLENESS LIMITS

No.	Parameter	Limits
1	Pressure Altitude	Greater than 27648 feet
2	Airspeed	Greater than 304 kts
3	Pitch Attitude	Greater than ±90°
4	Roll Attitude	Greater than ±90°
5	Collective Position	Outside of 1.5% to 98.5% of transducer range
6	Longitudinal Cyclic Position	
7	Lateral Cyclic Position	
8	Tail Rotor Pedal Position	
9	Normal CG Acceleration	Outside of -3.2 g to +5 g
10	Outside Air Temperature	Outside of ±64°C
11	Altitude Rate	Outside of ±8192 ft/min

Other parameters, such as the ARTNC 429 air data parameters, have validity bits associated with them. All synchro input parameters produce an abnormal periodic signal to alert the ground station that the excitation voltage for the synchro was not present. Synchro is a signal voltage indicating angular position as defined in ARINC STD 407.

2.3.5.2 Tightly Bounded FCR Algorithms.

The algorithms used for FCR will be developed such that the predefined limits for the principal data parameters used for each maneuver definition will have lower and upper bounds. If the conditions of the data parameters do not match any of the maneuvers, then the condition is classified as unrecognized.

An excessive amount of time spent in the unrecognized maneuver category is indicative of either a system problem or a maneuver that was not included in the original load-level survey. If an excessive amount of time in the unrecognized category is detected, then a parameter audit must be performed. If all usage parameters are found to be working properly, then the operator must have either performed a maneuver not in the load-level survey or there is an error in the algorithms for that maneuver. Continued excessive amount of time in the unrecognized category should be reported to Bell through normal product support channels. Bell will then review the time history data file to determine if the maneuver damage is covered by using the worst-case damage rate for each part on the aircraft. However, this will be an extremely improbable case, since maneuvers not included in the FCR recognition would have to be acrobatic in nature.

2.3.5.3 Parameter Correlation Checks.

The parameter correlation module will detect mean shifts in data that could result from a misrigged sensor. Mean shifts will be detected by correlating multiple parameters. Also, usage software will use the rate of change of the parameter data, instead of the raw parameter data to minimize the effect of mean shifts.

The parameter correlation module functions as follows.

- Primary parameters used for FCR identification of a maneuver will be checked against other secondary parameters not used for identification.

- The secondary parameter will be correlated to the primary parameter to check if the secondary parameter is in range.

- All primary and secondary parameter correlation data will be determined by analyzing actual flight test data from the M412 aircraft.

Figure 2-1 presents airspeed acceleration as an example of this kind of correlation. The rate of change of airspeed would be used to determine if the aircraft was accelerating and, at the same time, the collective could be checked for a corresponding change. This is just one example of the many different parameter checks that will be implemented.

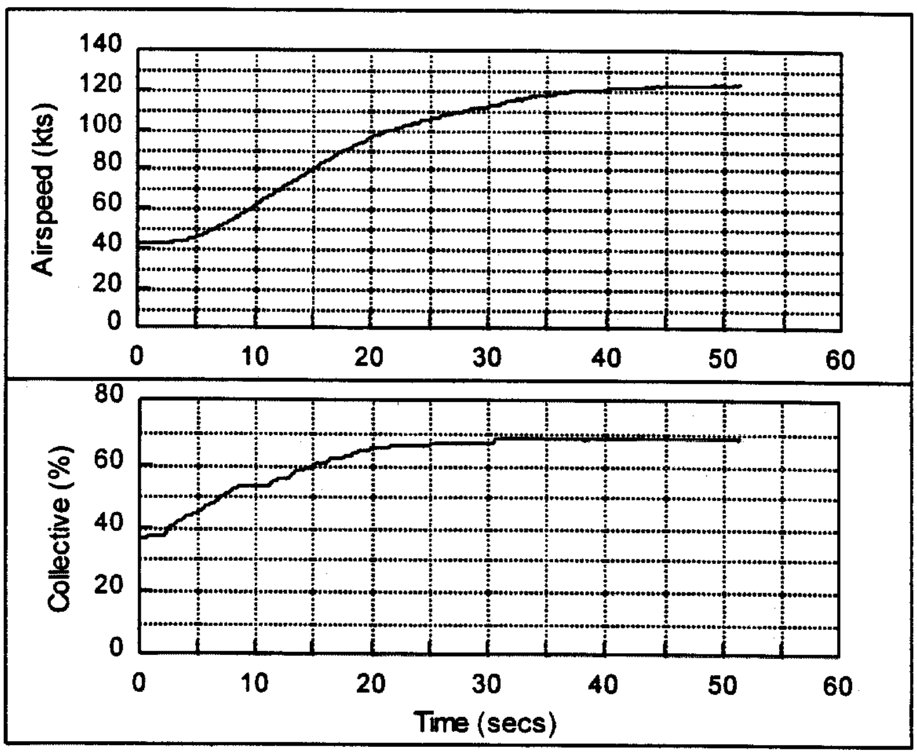

FIGURE 2-1. EXAMPLE OF PARAMETER COUPLING DURING AN ACCELERATION FROM CLIMB AIRSPEED TO V_h AIRSPEED

2.3.5.4 Usage Rate Check.

The test for abnormal component usage rates is based on a significant increase or decrease in the effective component life expended per flight hour. A database will be maintained within the usage ground station for each component part number that is tracked. This database will retain the effective component hours used per actual flight hour for each operation. If this rate of usage increases or decreases by a predefined factor, then the system operator would be prompted to determine if the mission profile had been significantly changed. Figure 2-2 presents an example of such a change.

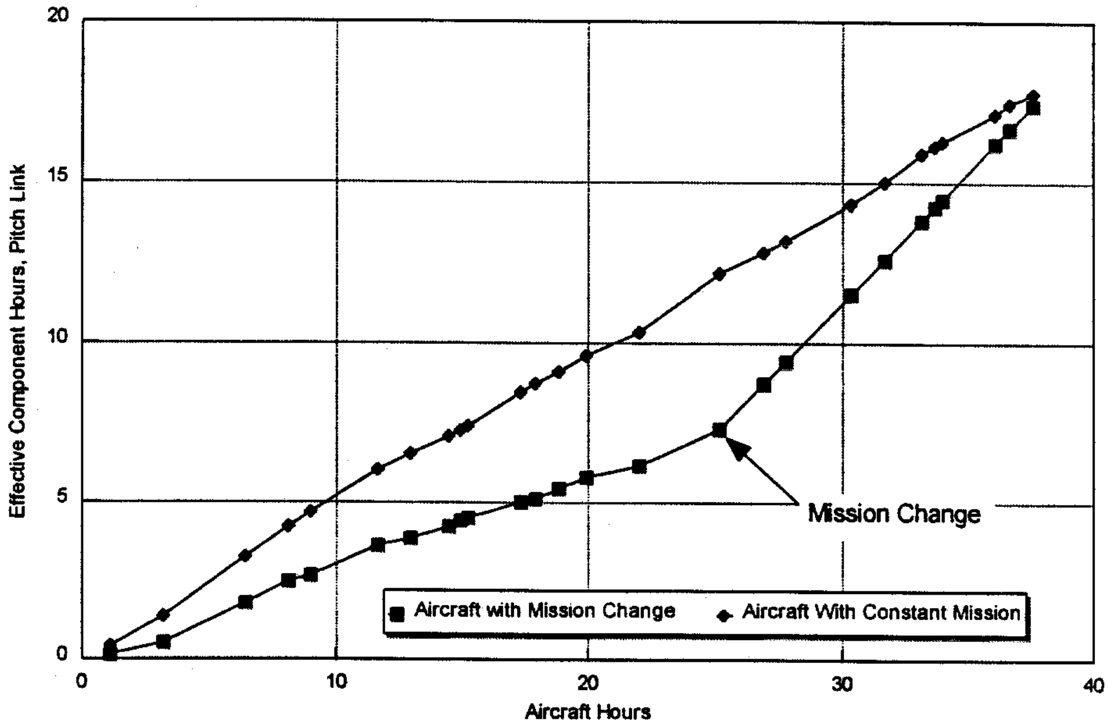

FIGURE 2-2. EXAMPLE OF USAGE RATE TRENDING

If the actual mission profile had not changed, a full HUMS system parameter audit and system integrity check would be required. If the checkout determined that incorrect data had been gathered by the HUMS, usage monitoring would revert to actual aircraft hours. This would be in lieu of FCR hours for the time period when the aircraft data were questionable. If the checkout found nothing wrong, then the data would be accepted as valid.

Possible causes of excessive changes to the usage rate could result from changes in flying style or the mission, the replacement of parts, or adjustments. Not finding any changes that could have affected the data, the operator will contact Bell for assistance in resolving the occurrence of abnormal component life consumption. Via the normal Bell product support process, the operator's data will be analyzed and the cause of the abnormality found.

3. MISSING DATA.

3.1 CAUSES.

Missing data can be caused by a variety of reasons. The major ones include:

- PC memory card failure or capacity exceeded during flight
- PC memory card not installed prior to flight or lost subsequently
- HUMS inoperative, malfunctioned or not installed

For these and all other possible causations not included in the above list, the process described below will detect any missing data.

3.2 DETECTING MISSING DATA.

Missing usage data can be detected by comparing the actual cumulative aircraft hours tracked by the airborne unit (parameter 20 in table 1-2) with the total time accumulated in the ground station by FCR usage processing. The cumulative aircraft hours maintained by the airborne unit are initialized from the logbook. If FCR time is less than actual aircraft hours, a time delta exists and usage data are missing.

A mitigating procedure has been included in the design to reduce the criticality of the software accounting for aircraft hours. A procedural check of actual aircraft flight hours as recorded in the aircraft logbook against usage data hours is accomplished by the logbook time audit.

3.3 LOGBOOK TIME AUDIT.

At a preset interval, the usage system administrator will enter the following data for the latest flight with the HUMS installed. These data are required so that the usage program can be certain that all of the actual aircraft hours have been accounted for.

- Aircraft hours from the logbook
- Date and landing time of last flight

The usage software will interrogate the usage database and compute the total cumulative usage hours processed and then compare that number to the hours from the logbook. If the usage hours processed are not equal to or greater than the logbook hours, then there are missing data. The missing data will be replaced with gap fill if the operator cannot find them.

If the usage hours exceed the actual aircraft hours by more than 2 percent, the process report will document this anomaly, but the effective hours for parts will not be reduced. This is because the logbook is considered the master record of flight hours and is correct by definition. Consequently, because the logbook hours are considered the authoritative source, component damage caused by excessive usage system hours are not removed from the damage accumulation.

3.4 GAP FILLING MISSING DATA.

To correct, or gap fill, missing data, a conservative time delta will be added to the time accumulated for each part monitored by the usage system. The missing data will be filled with actual flight hours or historical usage data whichever is worse. The gap-filled data will be tagged so that if the memory card containing the missing data is found, the gap-filled time can be removed and replaced with the time calculated by the usage system.

The system will also prompt the system operator to enter the number of flights conducted during this missing time. The system operator should also note any logging operation external lifts or hoist operations performed with the hoist installed in the right forward position in order to correct the RIN count (see sections 1.2.2 and 1.2.3 for more information).

4. WRONG ALGORITHMS.

There are three potential causes for the usage system to be implemented with wrong algorithms. These are (1) the specified algorithms were not translated into software requirements correctly, (2) the software requirements were not translated into design correctly, and (3) the design was not translated into code correctly. Once the code has been implemented, the testing process will verify that all the capabilities specified in the software requirements documentation will function as specified.

4.1 SOFTWARE REQUIREMENTS INCORRECT.

The software requirements will flow down from the System Requirements Document. Requirements traceability will be tracked through the development to ensure that all requirements are implemented.

4.2 SOFTWARE DESIGN INCORRECT.

The top level design is reviewed against the software requirements during a preliminary design review. Later in the design process, a detailed design review is held with the systems engineers, fatigue engineers, quality assurance, and others to review the detailed design against the requirements.

4.3 CODING ERRORS.

Individual programming team engineers will be responsible for coding the various units and modules of the software design. The team will then conduct a code walk-through of each portion of the design so that all members can contribute their individual experience to the overall design, and thus improve the software detail design and coding.

4.4 TESTING.

Test cases will be chosen to demonstrate that all the software requirements have been properly implemented. Any test failures will be analyzed and a determination made whether they affect the end product or not. Code involved in test failures will be fixed if necessary and retested. Other code, which may be affected by the changes, will also be retested. Any code changed after the code has been baselined will be written up and tracked using a Bell standard software problem report.

Flight testing will be undertaken to demonstrate that known flight regimes can be recognized by the usage software, and that the component damage is attributed accordingly. A flight test plan will be produced in which a scripted flight (or flights) will be conducted to provide known inputs for comparisons of the usage software results against the expected results. When the expected results are achieved, the algorithms will have been proven correct.

5. SYSTEM COMPLIANCE ASSESSMENT.

This section addresses issues of compliance with the usage application and the HUMS Advisory Circular. In particular, the compliance of sampling rates, system accuracy, the effects of gusts on the methodology, and system integrity and redundancy are discussed.

The list of required system parameters were shown in tables 1-2 and 1-3. For reference in this section, calculated root sum squared (RSS) accuracies, parameter rates, and sources are shown in table 5-1. Detailed calculations for the RSS parameter accuracies can be found in appendix A.

TABLE 5-1. USAGE PARAMETERS—ACCURACIES, RATES, AND SOURCES

No.	Parameter Name	RSS System Accuracy	Rate	Source
1	Pressure Altitude	40 ft	1 Hz	Air Data System[(1)]
2	Indicated Airspeed	1 knot	1 Hz	Air Data System[(1)]
3	Magnetic Heading	2.09°	4 Hz	Aircraft Instrument Sensor
4	Pitch Attitude	0.66°	4 Hz	Aircraft Instrument Sensor
5	Roll Attitude	0.66°	4 Hz	Aircraft Instrument Sensor
6	Normal Acceleration (Nz)	0.07 g /0.21 g max datum	8 Hz	Added HUMS Sensor
7	Main Rotor rpm	0.3%	2 Hz	Aircraft Instrument Sensor
8	Engine No. 1 Torque	1.13%	8 Hz	Aircraft Instrument Sensor
9	Engine No. 2 Torque	1.13%	8 Hz	Aircraft Instrument Sensor
10	Mast Torque (where applicable)	1.13%	8 Hz	Aircraft Instrument Sensor
11	Outside Air Temperature	2°C	1 Hz	Air Data System[(1)]
12	Altitude Rate (vertical velocity)	40 feet/minute	4 Hz	Air Data System[(1)]
13	Collective Stick Position	3%	4 Hz	HUMS System
14	F/A Cyclic Stick Position	3%	4 Hz	HUMS System
15	Lateral Cyclic Stick Position	3%	4 Hz	HUMS System
16	Tail Rotor Pedal Position	3%	4 Hz	HUMS System
17	Time and Date	System Setup	0.25 Hz	HUMS System
18	Pilot-Entered Gross Weight	50 lbs (Pilot Entry)	Once Per Flight[(2)]	Entered at Cockpit Display Panel[(3)]
19	On Ground Discrete	N/A	1 Hz	HUMS System
20	Aircraft Flight Hours	Audit to Pilot Logbook	1 Hz	HUMS System

(1) Dedicated air data computer for HUMS. Uses same pitot/static source as copilots display.

(2) The fuel burn algorithm will decrement gross weight as aircraft is in flight.

(3) If Pilot does not enter value, the system shall default to the gross weight causing the most damage for each component. Entry shall be reinitialized or entered again after each landing.

5.1 SAMPLING RATES.

The sampling rates that were chosen for each parameter were based on sensor signal characteristics and the software update rate. In current practice, flight time is accumulated by the pilot and is logged to the nearest minute. The Bell Usage Credit System logs flight regime data to a resolution of 1 second. The parameter acquisition rates were determined by assessing the response characteristics of the required sensor signals to dynamic changes in the flight regime responses. The minimum sample rate was therefore chosen to be 1 second for aircraft state parameters such as pressure altitude, airspeed, outside air temperature (OAT), and air/ground state discretes. Control position inputs, aircraft attitude, and heading rates were set at 4 Hz to allow the software to resolve and anticipate the flight regime changes required to meet the overall system resolution of 1 Hz. Engine torques, mast torque, and Nz, all of which have a direct effect on component damage are sampled at a rate of 8 Hz to provide a correct digital representation of the respective signals. Figure 5-1 shows that an 8-Hz sample rate is sufficient to capture a good digital representation of the torque signal.

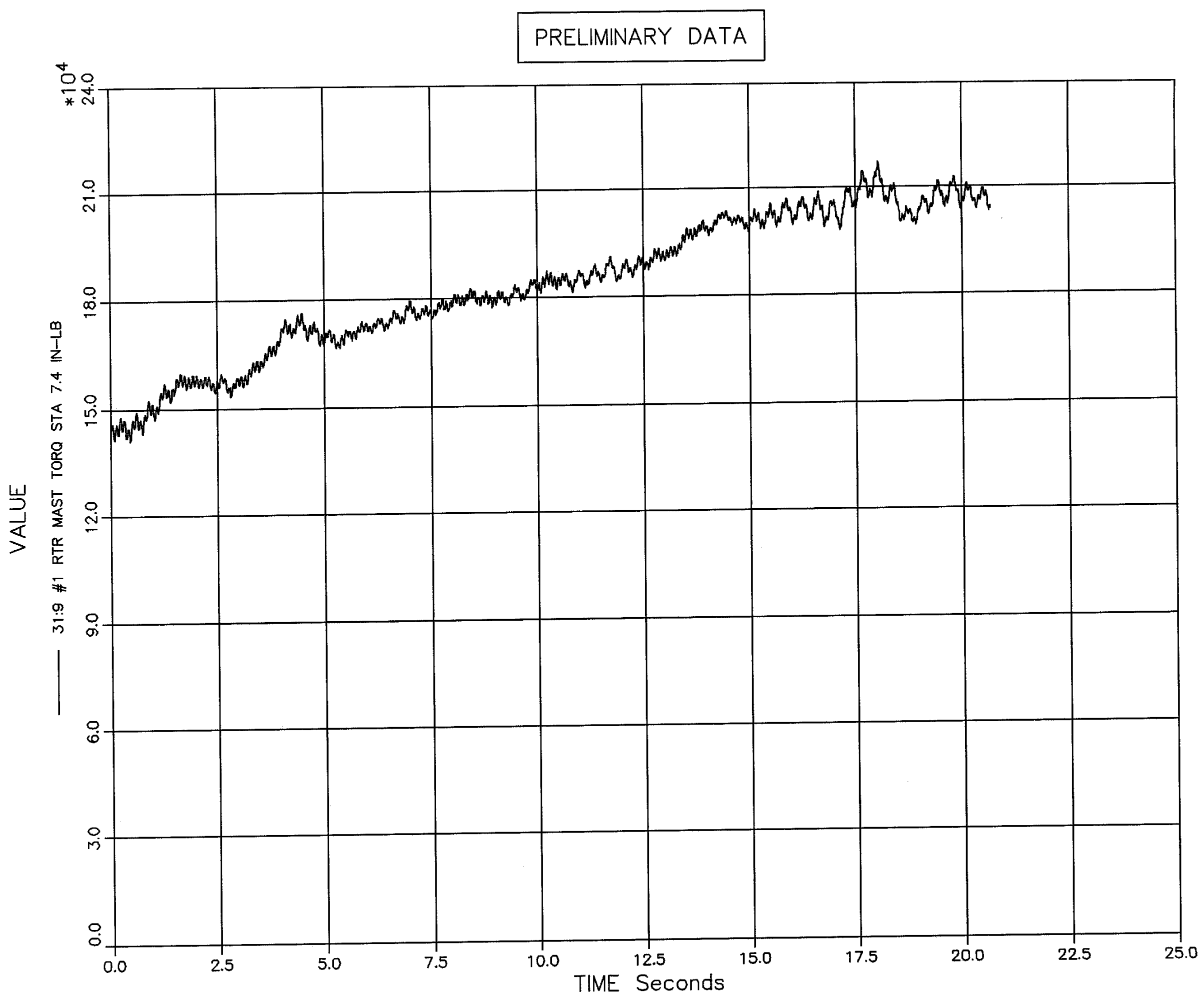

FIGURE 5-1. MODEL 412 HELICOPTER MAST TORQUE RESPONSE

5.2 SYSTEM ACCURACY.

The underlying accuracy of the HPU analogue acquisition is 0.2%. This is generally 5 to 10 times more accurate than the aircraft instruments. The true root mean square accuracies of the entire system, including the sensors, were given in table 5-1. For usage analysis, the basic requirement of the system is that the accuracy be much greater (e.g., 10X) than the bands that are used in the certification spectrum of the aircraft. This is very conservative since in Bell's proposed implementation of usage, all regimes are bumped up to the next level of the certification data. Assuming a uniform data distribution, the 10X accuracy goal means that 90% of the time the spectrum data will be put into the next higher band. For the remaining data points, the spectrum will be recorded in the existing band for a low-tolerance parameter. The basic design goal is to compute the individual aircraft spectrum into approximately 60 flight regimes with three gross weight bands for each flight regime in the certification load-level survey.

Table 5-2 presents a comparison of the calculated RSS accuracies of the usage parameters to the corresponding banding as applied to the regime definitions found in table 1-2. Banding is applicable to pressure altitude, airspeed, and gross weight. It is indirectly applicable to some additional calculations such as fuel burn corrections and calculations of V_h. Where banding is not applicable, the full-scale parameter accuracy is substituted.

TABLE 5-2. COMPARISON OF USAGE PARAMETER ACCURACY TO APPLIED SPECTRUM BANDING

No.	Parameter Name	RSS System Accuracy	Applied Banding	Accuracy as a Percent of Banding
1	Pressure Altitude	40 ft	3000 ft	1.3%
2	Indicated Airspeed	1 knot	12 knots	8.3%
3	Magnetic Heading	2.09°	360°	0.6%
4	Pitch Attitude	0.66°	90°	0.7%
5	Roll Attitude	0.66°	90°	0.7%
6	Normal Acceleration (Nz)	0.07g, 0.21 g max datum	-3 g, +6 g	0.8%, 2.3%
7	Main Rotor rpm	0.3% (1 rpm)	10 rpm	10%
8	Engine No. 1 Torque	1.13%	100%	1.13%
9	Engine No. 2 Torque	1.13%	100%	1.13%
10	Mast Torque (where applicable)	1.13%	100%	1.13%
11	Outside Air Temperature	2°C	N/A	Used to Calc Density Alt
12	Altitude Rate (vertical velocity)	40 feet/minute	600 feet/minute	6.7%
13	Collective Stick Position	3%	100%	Used to Validate FCR

TABLE 5-2. COMPARISON OF USAGE PARAMETER ACCURACY TO APPLIED SPECTRUM BANDING (Continued)

No.	Parameter Name	RSS System Accuracy	Applied Banding	Accuracy as a Percent of Banding
14	F/A Cyclic Stick Position	3%	100%	Used to Validate FCR
15	Lateral Cyclic Stick Position	3%	100%	Used to Validate FCR
16	Tail Rotor Pedal Position	3%	100%	Used to Validate FCR
17	Time and Date	System Setup	N/A	See item 20
18	Pilot-Entered Gross Weight	50 lbs (Pilot Entry)	2000 lbs	2.5%
19	On Ground Discrete	N/A	N/A	
20	Aircraft Flight Hours	Audit to Pilot Logbook	N/A	Logbook Audit

Additional parameters are derived as referenced in table 1-3. These parameters are of four types: (1) the rates of change in airspeed, heading, pitch, and roll that are used for validating the transitions to various flight conditions, (2) engine transition states based on simple engine torque logic, (3) peak and valley algorithms for the controls, and (4) two additional derived parameters that are of importance, the initial gross weight and V_h. It should be noted that

- Initial gross weight is corrected for fuel burn based on OAT, engine torques, and pressure altitude. This is a conservative calculation that is found in the Bell 412 Flight Manual.

- V_h is calculated as a function of altitude and gross weight. The original spectrum is divided into conditions of 0.4, 0.6, 0.8, 0.9, and 1.0 V_h. V_h is a function of density altitude (pressure altitude and OAT) and gross weight. V_h is originally determined by measurement during the load level survey for the original usage spectrum. A worst-case analysis was made to determine the worst-case accuracy of V_h based on variations in pressure altitude, OAT, and gross weight. The results were good with a worst-case accuracy of less than 2% up to 12,000 ft, and less than 3% error at 15,000 ft. For most of these regions, the worst-case errors were actually less than 0.5%. The detailed error analysis for V_h can be found in appendix B.

It should further be noted that the nominal value of V_h that is calculated with this expression is approximately 6 knots below the Flight Manual Values. This adds additional conservatism to the usage calculations.

5.3 THE EFFECT OF GUSTS.

Wind gusts do affect the loads on helicopter dynamic components. This effect is accounted for in two ways. First, the load-level survey is flown in real conditions. While no effort is made to specifically seek turbulent air, there is also no effort to avoid it unless it directly conflicts with hitting a target, e.g., a very specific airspeed and second by performing control reversals. Control reversals, which are designed to simulate a pilot's response to wind gusts, consist of rapid oscillations of the fore and aft, lateral, and pedals, each of which is performed individually. Control reversals are typically flown at both high speed and hover. This approach to handling the effect of gusts is part of the original load-level analysis and is not altered by the application of the current methodology for usage.

5.4 SYSTEM INTEGRITY AND REDUNDANCY.

System integrity and redundancy, which are covered in sections 2, 3, and 4, include three areas of concern: inaccurate data, missing data, and wrong algorithms. The proposed usage methodology addresses all of these possible integrity issues without the need for any hardware or software redundancy.

6. USAGE METHODOLOGY.

This section contains an outline of the end-to-end process being proposed for usage monitoring, including airborne operation and all aspects of ground-based processing. A chart showing the data flow for the portions of this process that are carried out in the ground station is presented in figure 6-1. Note that the maintenance data tracking facility responsibilities are not part of the Bell usage system but are functions of the operator's existing system.

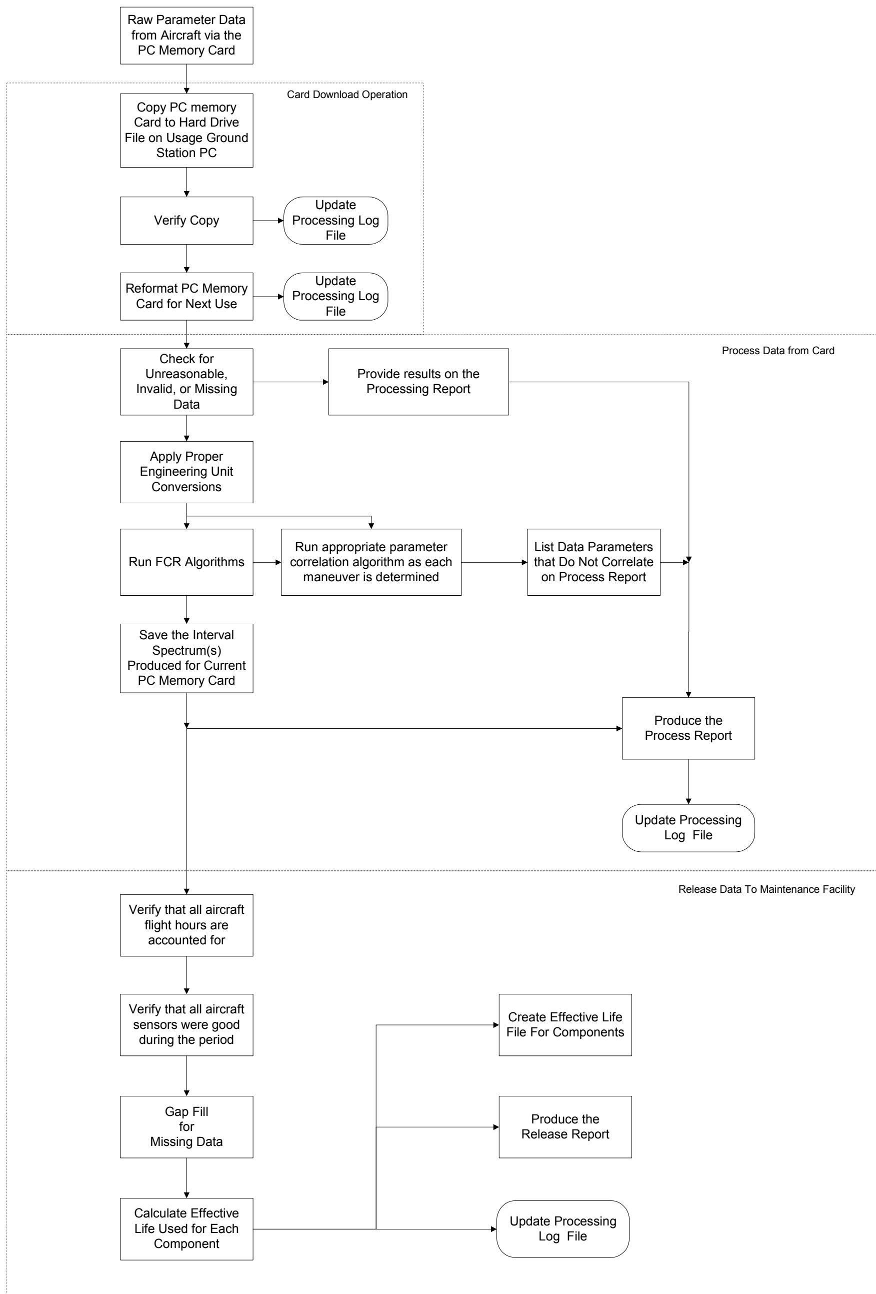

FIGURE 6-1. FLOWCHART OF DATA FLOW IN THE USAGE GROUND STATION

Also included in this section is a discussion of some of the more important aspects of the methodology. Policies and procedures that an operator must comply with in order to utilize usage credits will be contained in the Usage System Operation Manual. These policies and procedures will expand upon all user actions mentioned in this report; in particular, the methodology that is presented in the following sections.

6.1 USAGE PROCESS.

The end-to-end process is as follows:

a. Install the PC memory card in the HUMS-equipped aircraft
b. Conduct aircraft operations
c. Remove the PC memory card and deliver it to the usage ground station
d. Perform the card download operation by:

- copying the PC memory card data to the usage hard drive.
- confirming the data copy and preparing the PC memory card for its next use.

e. Process data from the memory card by:

- checking for unreasonable, invalid, or missing data; apply engineering units.
- running the FCR algorithms and correlate the appropriate parameters for each maneuver identified.
- creating an interval spectrum for each operation, and save the accumulated interval spectrums until the next data release.
- Computing the life expended for all operations on this PC card by trending the usage rate. If there are unacceptable shifts in the trends, require interviews with pilot(s) and maintainer(s) about past missions versus present missions. If there was no mission or aircraft change, then require a full parameter audit.
- producing a Process Report for the PC memory card data processed in which the anomalies and actions that should be taken are listed, including the parameters that should be audited from the parameter correlation checks.
- checking for excessive time in the unrecognized flight regime, and requesting a full system parameter audit, if required, and developing a reminder message for monthly audits, checks, or system calibrations.

f. If a parameter audit was performed, have user input the results
g. If a system integrity check was performed, have user input the results
h. When an aircraft logbook audit is performed, make sure all flight hours are accounted for
i. Release data to a maintenance data-tracking facility in which:

- gap fill for missing data (including where data was found invalid or unreasonable) will be made.

- a Release Report will be produced in which each operation processed will include the operation time (flight time for each operation), the number of flights, and the damage to the parts for each operation.

The maintenance data-tracking facility, which is not part of the Bell usage system, (1) receives component usage data from the ground station for a release cycle, (2) accumulates component usage over the life of the component, (3) maintains aircraft configuration, and (4) reports to the maintainer when a part should be replaced.

6.2 RELEASE OF DATA.

When the system administrator wishes to prepare a report of effective incremental damage hours for all the components of a particular aircraft, then the following list of items will be checked internally by the usage software.

- Can the logbook time be verified with the processed time?
- Are all the gaps in the data filled?
- Has the parameter audit been completed?
- Have all anomalies reported by process reports been explained or corrected?

Effective component hours will be considered valid for only the operations through the point in time at which (1) the last parameter audit was completed, (2) the last logbook time verification was completed, and (3) all anomalies were explained or corrected. A Release Report will then be issued.

The Release Report will have two forms, one suitable for review and audit by the system administrator, and one suitable for transfer to the operator's maintenance data-tracking facility.

6.3 EFFECTIVE HOURS CALCULATION.

Effective component hours are defined as the component life expended in accordance with HUMS usage algorithms. This value will be expressed in terms such that the original retirement life of the part established by the manufacturer will still be used. This methodology will allow operators to retain their current systems for tracking cumulative hours used on components, and allow components from a non-HUMS aircraft to be moved to a HUMS aircraft and vice versa. Aircraft conditions will be tracked by the number of events that have occurred or by time in a flight condition. The total effective component hours can be expressed in general as

$$\begin{aligned}\textit{Total Effective Component Hours} &= (\textit{Effective Component Hours})_{Time} + (\textit{Effective Component Hours})_{Event} \\ &= \sum(\textit{Time in Flight Condition x Component Hours Used per flight condition}) \\ &\quad + \sum(\textit{Number of Events x Component Hours Used per Event})\end{aligned}$$

In these relations, time-in-flight condition denotes the total minutes that are spent in each flight condition, component hours used per flight condition is the equivalent hours of a given component's life used per minute in that flight condition, number of events is the total number of given events performed during an operation, and component hours used per event is the equivalent hours of a given component's life used per event.

In most cases, the value of the effective hours is based either on a time-based or an event-based calculation. In a very few cases, these two methods are combined, as shown in the above equation. However, most often the individual terms of this equation are used to calculate either a time-based or an event-based number of effective hours.

As an illustrative example, consider a flight that included 10 minutes of flight condition A for which the component hours established during the original flight loads survey of the aircraft for part X would be 0.7. Then, the effective component hours for that part in that flight would simply be (10/60) x 0.7 = 0.117 hrs. This process would then be repeated for each condition, with the results summed to obtain the effective component hours for part X.

There will be a unique component hours used per flight condition or component hours used per event value for each component and flight condition combination. These values will be calculated using the same certification flight load-level survey data [5] and certification fatigue strength data [7] for the model 412 aircraft.

6.4 FLIGHT CONDITION RECOGNITION ALGORITHMS.

Algorithms for FCR will be designed on a decision tree approach, with most decisions involving the test of either a measured or a derived parameter against a normal range. The normal ranges for the parameters have been established by the value of each parameter in steady-state conditions of level flight or hover. The normal ranges for the parameters are presented in table 6-1. An example of what may be used for the main decision module is presented in figure 6-2. Once a submodule has been entered, appropriate aircraft parameters, or combinations of parameters, are tested to determine if the aircraft is in a climb, dive, left or right turn, pull-up, etc.

TABLE 6-1. NORMAL RANGES OF PARAMETERS

Parameter	High Value	Low Value
Pitch Attitude	15 deg	-15 deg
Pitch Rate	+3.5 deg/sec	-2.0 deg/sec
Roll Attitude	+4 deg	-4 deg
Roll Rate	+4 deg/sec	-4 deg/sec
Normal Acceleration (Nz)	+1.3 g's	+0.8 g
Main Rotor RPM	339 rpm	300 rpm
Altitude Rate (vertical velocity)	600 ft/min	-600 ft/min
Collective Stick Position	105%	15%
F/A Cyclic Stick Position	20%	-80%
Lateral Cyclic Stick Position	50%	-50%
Tail Rotor Pedal Position	40%	-40%
Rate of Change Magnetic Heading	+4 deg/sec	-4 deg/sec

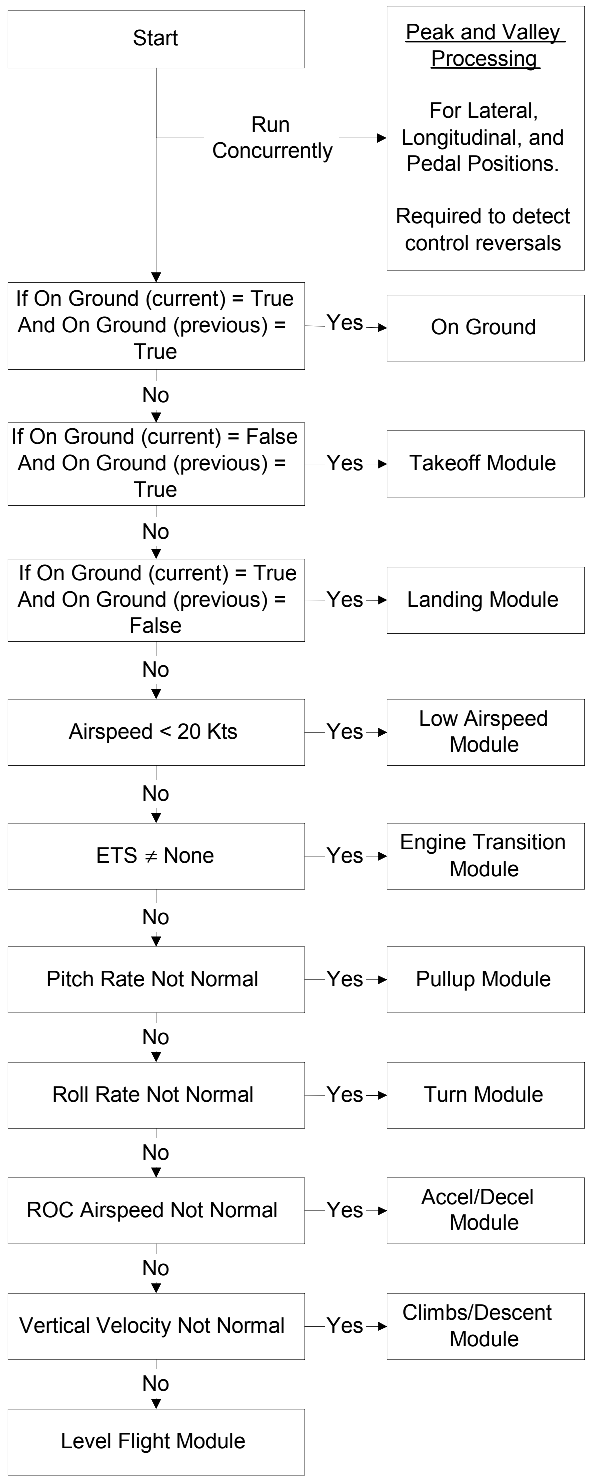

FIGURE 6-2. MAIN FCR DECISION MODULE

7. USAGE SYSTEM SOFTWARE CONSIDERATIONS.

7.1 USAGE SYSTEM CHECKS AND BALANCES.

In order to lower the usage software's contribution to the overall system failure probability, monitoring algorithms will be implemented to crosscheck the usage algorithms. These include usage rate check, parameter correlation checks, and parameter validity checks. These algorithms are discussed in section 2.3.5, Process Report.

Procedures have been included in the system design to further lower the usage software's contribution to the overall system failure probability. These include review of the process report (see section 2.3.5), review of the release report (see section 2.3.4), the parameter audit (see section 2.3.l), the logbook audit (see section 3.3), the tape backup (see section 2.3.2), and the usage system integrity check (see section 2.3.3).

7.2 USAGE SYSTEM OPERATING SYSTEM.

The operating system for the usage monitoring system ground station will be Windows NT, as suggested in section 2.2.2.

7.3 USAGE SYSTEM SOURCE CODE.

The source code for the usage system software will be written in a high-level language. High-level languages typically provide for strong type checking and structured language constructs that provide a more maintainable end product and with reduced errors during development.

7.4 THE FCR ALGORITHM PROTOTYPING USING STAND ALONE SOFTWARE.

All usage algorithms will be prototyped and then tested using existing flight test data from an aircraft instrumented to record parameter data required for FCR. During these flight test data flights, the maneuvers performed should be documented in the pilot's log.

7.5 LOCAL DATABASE.

The Bell usage credit system includes two databases and a configuration change file. A spectrum database will be maintained for each aircraft that is monitored with a usage system. The data will consist of (1) the cumulative spectrum, (2) effective hours for each operation and part combination for all operational time since the two previous logbook and parameter audits, (3) all files which contain parameter data for instances of unrecognized data, and (4) the usage rate per component for each aircraft.

An aircraft configuration database will be included within the system. The configuration database will contain all aircraft in the usage monitoring program along with the part numbers and serial numbers of all usage components. This database will contain actual aircraft hours, effective hours, and total hours gap-filled for all the aircraft and components being monitored.

In addition to the configuration database, an electronic log file will be maintained of all component changes made on each aircraft. The file will include the aircraft serial number, change date, change time, component part numbers and serial numbers for the removed and added components, component disposition, and aircraft flight hours at the time of the change.

7.6 LEVEL OF COMPLIANCE WITH RTCA/DO-178B.

The usage application software will be developed and tested to the guidelines of the HUMS Advisory Circular and RTCA/DO-178B. A usage credit application falls into the 1309 criticality category of hazardous/severe/major.

Mitigation of the airborne software criticality is achieved through initial system calibration and periodic parameter audits. In the proposed application, this mitigation reduces the required airborne software level for flight parameter acquisition from Level B to Level C.

The HUMS Advisory Circular does not allow a similar mitigation for the ground station application software due to the use of COTS hardware and software. Therefore, the usage application software must be developed in accordance with RTCA/DO-178B, Level B. This hazard assessment shows the software contribution of the usage application software to meet or exceed the guidelines of the Advisory Circular.

The integrity of the COTS software and hardware is assured (per the HUMS Advisory Circular) through use of an independent means of verification during the introduction to service period.

8. SUMMARY.

This report collects data and other information that have been developed by Bell Helicopter Textron for its Health and Usage Monitoring System (HUMS) applications, and provides it in a systematic manner to support more general and informed use of this important technology. A detailed overview of the HUMS methodology is provided first in this report that describes how flight condition recognition (FCR) is used to determine an individual aircraft load spectrum that, in turn, is used to calculate the effective hours that correspond to this usage. The report then focuses on sources of error in usage monitoring and how these can be overcome. These include inaccurate data, missing data and incorrect algorithms. Next, system compliance with usage applications is discussed. Finally, a prototype usage system for implementing and using HUMS is outlined. The prototype usage system has been evaluated for compliance with the HUMS Advisory Circular. This analysis verified that the prototype system and its architecture are compliant with the intent of the advisory circular, including required parameter rates and accuracy levels. This report provides a valuable resource for usage monitoring that can both increase safety and enhance more economical operations, while also providing the basis for the eventual linkage of HUMS with the rotorcraft damage tolerance methodology.

9. REFERENCES.

1. DOT/FAA/AR-95/9, February 1996, "Feasibility Study of a Rotorcraft Health and Usage Monitoring System (HUMS): Usage and Structural Life Monitoring Evaluation" and

2. DOT/FAA/AR-95/50, February 1996, "Feasibility Study of a Rotorcraft Health and Usage Monitoring; system (HUMS): Results of Operator's Evaluation."

3. Amendment 29-l 9 Advisory Circular, Number 29 -2A, Paragraph 621 "29.1309 (through Amendment 29-19) EQUIPMENT, SYSTEMS, AND INSTALLATIONS."

4. DOCUMENT NO. RTCWDO-178B, "Software Considerations in Airborne Systems and Equipment Certification."

5. BHTI Report No. 412-910-001, "Flight Loads Survey for the Model 412 Helicopter."

6. BHTI Report No. 412-099-353, "Hazard Analysis for the Installation of Teledyne/Stewart Hughes HUMS in the Bell Model 412EP."

7. BHTI Report No. 412-910-006, "Fatigue Substantiation of the Dynamic Components for the Model 412 Helicopter."

APPENDIX A—412 HUMS USAGE PARAMETER ACCURACIES

A-1 PRESSURE ALTITUDE ACCURACY.

The performance specifications were obtained from section 2.2 of the Shadin Installation Manual (Rev A, Report Number 4028D dated August 20, 1998) in order to identify the error contribution of the air data computer. The accuracy analysis consisted of the following.

- Accuracy ±25 ft from -1000 ft to 5000 ft
  ±30 ft from 5,000 ft to 11,000 ft
  ±40 ft from 11,000 ft to 30,000 ft

For comparison purposes, the requirement specified in Title 14 Code of Federal Regulations (CFR) Part 135, Appendix C is ±100 ft to ±700 ft.

Note: Altitude is not derived from an existing aircraft signal source, and subsequently, the requirement in note 1 of 14 CFR Part 135, Appendix C does not apply.

A-2 INDICATED AIRSPEED ACCURACY.

The performance specifications were obtained from section 2.2 of the Shadin Installation Manual (Rev A, Report Number 4028D dated August 20, 1998) in order to identify the error contribution of the air data computer. The accuracy analysis consisted of the following.

- Accuracy ±1.0 Kt.

For comparison purposes, the requirement specified in 14 CFR Part 135, Appendix C is ±5% or 10 Kt.

Note: Altitude rate is not derived from an existing aircraft signal source, and subsequently, the requirement in note 1 of 14 CFR Part 135, Appendix C does not apply.

A-3 MAGNETIC HEADING ACCURACY.

The performance specifications were obtained from the Honeywell TARSYN-H System Maintenance Manual in order to identify the error contribution of the Directional Gyro. The performance information for the HUMS processing unit (HPU) was obtained from the Teledyne System Requirements Specification. The accuracy analysis consisted of the following:

From table 2-11 of the Honeywell Maintenance Manual 22-15-03, page 2-51 dated June 1, 2000:

- Accuracy ±2.0° (slaved accuracy)

The input of the HPU (reference channel #34 of SRS 2237400-1 page C-3) is identified as a synchro-type input where the accuracy of that input type is specified in paragraph 3.2.1.2.3 of SRS 2237400-1, sheet 32. All errors within the HPU identified as a root sum squared (RSS) value of ±0.17% full scale.

The synchro input scaling within the HPU (reference SRS 2237400-1, sheet 18) is scaled for 359.912° (4095 counts) full scale. Subsequently, the full-scale HPU accuracy is

$$\frac{0.17\%}{100\%} \times 359.912° = \pm 0.612°$$

The system accuracy is then obtained by the following:

$$\text{System Accuracy (RSS)} = \sqrt{(0.612)^2 + (2.0)^2} = \pm 2.09°$$

For comparison purposes, the requirement specified in 14 CFR Part 135, Appendix C is ±5°.

Note: The contribution of the HPU accuracy is 29% in reference to note 1 in 14 CFR Part 135, Appendix C.

A-4 PITCH ATTITUDE ACCURACY.

The performance specifications were obtained from the Honeywell TARSYN-H System Maintenance Manual in order to identify the error contribution of the Vertical Gyro. The performance information for the HUMS processing unit (HPU) was obtained from the Teledyne System Requirements Specification. The accuracy analysis consisted of the following.

From Table 2-11 of the Honeywell Maintenance Manual 22-15-03, page 2-51, dated June 1, 2000:

- Accuracy ±0.25° (labeled verticality error)

Note: For validation of the accuracy, Honeywell engineering specification CP 2593996 was reviewed and the test limits verified the ±0.25°.

The input of the HPU (reference channel #33 of SRS 2237400-1 page C-3) is identified as a synchro-type input where the accuracy of that input type is specified in paragraph 3.2.1.2.3 of SRS 2237400-1, sheet 32. All errors within the HPU identified as an RSS value of ±0.17% full scale.

The synchro input scaling within the HPU (reference SRS 2237400-1, sheet 18) is scaled for 359.912° (4095 counts) full scale. Subsequently, the full-scale HPU accuracy is

$$\frac{0.17\%}{100\%} \times 359.912° = \pm 0.612°$$

The system accuracy was then obtained by the following

$$\text{System Accuracy RSS} = \sqrt{(0.612)^2 + (2.0)^2} = \pm 0.66°$$

For comparison purposes, the requirement specified in 14 CFR Part 135, Appendix C is ±2°.

Note: The contribution of the HPU accuracy is 92.7% in reference to note 1 in 14 CFR Part 135, Appendix C.

A-5 ROLL ATTITUDE ACCURACY.

The performance specifications were obtained from the Honeywell TARSYN-H System Maintenance Manual in order to identify the error contribution of the Vertical Gyro. The performance information for the HPU was obtained from the Teledyne System Requirements Specification. The accuracy analysis consisted of the following.

From Table 2-11 of the Honeywell Maintenance Manual 22-15-03, page 2-51, dated June 1, 2000:

- Accuracy ±0.25° (labeled verticality error)

Note: For validation of the accuracy, Honeywell engineering specification CP 2593996 was reviewed and the test limits verified the ±0.25° accuracy.

The input of the HPU (reference channel #35 of SRS 2237400-1 page C-3) is identified as a synchro-type input where the accuracy of that input type is specified in paragraph 3.2.1.2.3 of SRS 2237400-1, sheet 32. All errors within the HPU identified as an RSS value of ±0.17% full scale.

The synchro input scaling within the HPU (reference SRS 2237400-1, sheet 18) is scaled for 359.912° (4095 counts) full scale. Subsequently, the full-scale HPU accuracy is

$$\frac{0.17\%}{100\%} \times 359.912° = \pm 0.612°$$

The system accuracy was then obtained by the following

$$\text{System Accuracy RSS} = \sqrt{(0.612)^2 + (0.25)^2} = \pm 0.66°$$

For comparison purposes, the requirement specified in 14 CFR Part 135, Appendix C is ±2°

Note: The contribution of the HPU accuracy is 92.7% in reference to note 1 in 14 CFR Part 135, Appendix C.

A-6 NORMAL ACCELERATION ACCURACY (Nz).

The performance specifications were obtained from Patriot CMM, 31-33-15, revision dated 05/94, page 3 component maintenance manual, in order to identify the error contribution of the accelerometer. The performance information for the HPU was obtained from the Teledyne System Requirements Specification. The accuracy analysis consisted of the following.

- Accuracy — Review of the accuracy requirement shows the sensor tolerance ±0.75% full scale.

  The sensor range specified is -3 to +6 g or 9 *g*

  The sensor portion of the system accuracy is then:

  $$\text{Sensor Accuracy} = \frac{0.75}{100} \times 9\,g\ \text{(full range)} = \pm 0.068\,g$$

  The additional sensor errors due to axial null and thermal null shift were stated as follows:

  $$\text{The scaling is then } \frac{5.0\,Vdc}{9.0\,g} = 0.56\ Vdc/g$$

  $$\text{Axial null tolerance specified} = \pm 0.025\ Vdc \text{ or } \frac{0.025\,Vdc}{0.56\,Vdc/g} = \pm 0.045\,g$$

  Thermal null shift = ±0.01% fs per degree F from -65° to 160°F 225°F × 0.01 = ±2.25%

  $$\text{or } \frac{2.25}{100} \times 9\,g = \pm 0.203\,g$$

  $$\text{Sensor RSS accuracy (max. datum)} = \sqrt{(0.045)^2 + (0.203)^2} = \pm 0.208\,g$$

The input of the HPU (reference channel #1 (Normal) of SRS 2237400-1 page C-2) is identified as a low level DC (LLDC)-type input where the accuracy of that input type is specified in paragraph 3.2.1.2.3 of SRS 2237400-1, sheet 32.

All errors within the HPU identified as an RSS value of ±0.2% full scale, which translates to

$$\frac{0.2}{100} \times 9\,g = \pm 0.018\,g$$

The LLDC input scaling within the HPU (reference SRS 2237400-1, sheet 18) is scaled for 5 Vdc (4095 counts) full scale or 9 *g*.

The system accuracy was then obtained by the following:

$$\text{System Accuracy RSS} = \sqrt{(0.068)^2 + (0.018)^2} = \pm 0.07\,g$$

For comparison purposes, the requirement specified in 14 CFR Part 135, Appendix C is ±0.2 *g*.

The maximum datum error system accuracy was then obtained by the following

$$\text{Max Datum RSS} = \sqrt{(0.208)^2 + (0.018)^2} = \pm 0.209\,g$$

For comparison, the requirement specified in 14 CFR Part 135, Appendix C is ±0.3 *g* maximum datum error.

Note: The contribution of the HPU accuracy is 25.7% in reference to note 1 in 14 CFR Part 135, Appendix C.

A-7 MAIN ROTOR SPEED ACCURACY.

The performance requirements for the tachometer generators are identified in MIL-G-26611. Review of this document revealed that the error contribution of the tachometer generator is primarily mechanical (i.e., gearbox, transmission pad, etc.) relative to speed accuracy and, subsequently, beyond the scope of this analysis. The performance information for the HPU was obtained from the Teledyne System Requirements Specification. The accuracy analysis consisted of the following.

The input of the HPU (reference channel frequency #1 of SRS 2237400-1 page C-4) is identified as a slow tach-type input where the accuracy of that input type is specified in paragraph 3.2.1.2.3 of SRS 2237400-1, sheet 32. All errors within the HPU identified as an RSS value of ±0.25% full scale.

The slow tach (period measurement) input scaling within the HPU (reference SRS 2237400-1, sheet 18) is scaled from 7 Hz (1 count) to 250 Hz (4095 counts) full scale. As identified above, the full-scale HPU accuracy is

±0.25% of 120% or ±0.3% full scale

Because the error contribution is strictly due to the HPU, the HPU accuracy becomes the total system accuracy.

For comparison, the requirement specified in 14 CFR Part 135, Appendix C is ±5%.

Note: The contribution of the HPU accuracy is 100% in reference to note 1 in 14 CFR Part 135, Appendix C.

A-8 ENGINE/MAST TORQUE ACCURACY—ENGINES 1&2& MAST.

The following paragraphs identify the accuracy, range, sampling interval, and resolution for engine torque.

1. Engine Torque—Bell 412 serial numbers (S/N) 33001 through 33213 and 36001 through 36019

    - Engine Torque Accuracy

Note: This sensor is installed in the above referenced S/N aircraft except for those aircraft modified with the improved hover performance kit (Bell P/N 412-570-001-103).

The performance specifications were obtained from Courter Inc. (Bendix) 172-1842-7 corresponding to Bell Sensor P/N specification 412-075-205 in order to identify the error contribution of the torque pressure transducer. The performance information for the HPU was obtained from the Teledyne System Requirements Specification. The accuracy analysis consisted of the following

From Courter Inc. (Bendix) drawing 172-1842-7, Revision N, dated 10/21/82, Table I:

- Accuracy

Note: Review of the accuracy presented in Table I shows a bell shape curve with accuracies ranging from ±2.5° @ 0 psi, ±0.7° @ 35psi to ±2.2° @ 65 psi. The accuracies were presented as percent of point rather than percent of full scale. Given that the range generally will be between 20 psi and higher, and to be conservative, the tolerance at that point (20 psi) was used (±1.5°). Therefore:

The sensor accuracy is then $\frac{1.5}{69.6} \times 100 = \pm 2.16\%$

The input of the HPU (reference channels #42 and #43 of SRS 2237400-1 page C-3) is identified as a synchro-type input where the accuracy of that input type is specified in paragraph 3.2.1.2.3 of SRS 2237400-1, sheet 32. All errors within the HPU identified as an RSS value of ±0.17% full scale.

The synchro input scaling within the HPU (reference SRS 2237400-1, sheet 18) is scaled for 359.912° (4095 counts) full scale.

The system accuracy was then obtained by the following

$$\text{System Accuracy RSS} = \sqrt{(2.16)^2 + (0.17)} = \pm 2.167\%$$

For comparison purposes, the requirement specified in 14 CFR Part 135, Appendix C is ±5%.

Note: The contribution of the HPU accuracy is 7.8% in reference to note 1 in 14 CFR Part 135, Appendix C.

<u>A-9 OUTSIDE AIR TEMPERATURE ACCURACY</u>.

The performance specifications were obtained from Shadin in order to identify the error contribution of the air data computer. The accuracy analysis consisted of the following.

From section 2.2 of the Shadin Installation Manual (Rev A, Report Number 4028D dated August 20, 1998) and supported by additional data from Shadin:

- Accuracy ±2°C

A-10 ALTITUDE RATE ACCURACY.

The performance specifications were obtained from Shadin in order to identify the error contribution of the Air data computer. The accuracy analysis consisted of the following.

From section 2.2 of the Shadin Installation Manual (Rev A, Report Number 4028D dated August 20, 1998) and supported by additional data from Shadin:

- Accuracy ±40 ft/min

For comparison purposes, the requirement specified in 14 CFR Part 135, Appendix C is ±250 ft/min below 12,000 ft altitude and ±10% above 12,000 ft altitude.

Note: Altitude rate is not derived from an existing aircraft signal source, and subsequently, the requirement in note 1 of 14 CFR Part 135, Appendix C does not apply.

A-11 COLLECTIVE POSITION ACCURACY.

The performance specifications were obtained from the Bell Sensor drawing P/N 412-074-101 in order to identify the error contribution of the control motion transducer. The performance information for the HPU was obtained from the Teledyne System Requirements Specification. The accuracy analysis consisted of the following.

From Bell Specification 412-074-101, Rev E, dated 2/11/93:

- Accuracy Review of the performance data in Note 2, Item A1, shows the resistance tolerance over the entire environmental range is ±15%. The linearity tolerance, indicated in A-2 is ±0.5% over the entire operating range.

The nonrigged sensor accuracy is then

$$\text{Sensor RSS accuracy (nonrigged)} = \sqrt{(15.0)^2 + (0.5)^2} = \pm 15.01\%$$

Note: The accuracy above does not include the mechanical misalignment due to mechanical tolerance in the sensor package.

The input of the HPU (reference channel #6 of SRS 2237400-1 page C-2) is identified as a potentiometer (POT)-type input where the accuracy of that input type is specified in paragraph 3.2.1.2.3 of SRS 2237400-1, sheet 32. All errors within the HPU identified as an RSS value of ±0.2% full scale.

The POT input scaling within the HPU (reference SRS 2237400-1, sheet 19) is scaled for 5 Vdc (4095 counts) full scale.

The system accuracy was then obtained by the following.

$$\text{System Accuracy RSS} = \sqrt{(15.01)^2 + (0.2)^2} = \pm 15.01\%$$

For comparison, the requirement specified in 14 CFR Part 135, Appendix C is ±3%.

Note: The contribution of the HPU accuracy is 1.3% in reference to note 1 in 14 CFR Part 135, Appendix C.

Installed Accuracy: The Collective position sensor is rigged per procedure to be within ±3% of Travel.

A-12 F/A CYCLIC POSITION (LONGITUDINAL) ACCURACY.

The performance specifications were obtained from the Bell Sensor drawing P/N 412-074-101 in order to identify the error contribution of the control motion transducer. The performance information for the HPU was obtained from the Teledyne System Requirements Specification. The accuracy analysis consisted of the following.

From Bell Specification 412-074-101, Rev E, dated 2/11/93:

Accuracy Review of the performance data in Note 2, Item A1, shows the resistance tolerance over the entire environmental range is ±15%. The linearity tolerance, indicated in A-2 is ±0.5% over the entire operating range.

The nonrigged sensor accuracy is then

$$\text{Sensor RSS accuracy (nonrigged)} = \sqrt{(15.01)^2 + (0.2)^2} = \pm 15.01\%$$

Note: The accuracy above does not include the mechanical misalignment due to mechanical tolerance in the sensor package.

The input of the HPU (reference channel #6 of SRS 2237400-1 page C-2) is identified as a POT-type input where the accuracy of that input type is specified in paragraph 3.2.1.2.3 of SRS 2237400-1, sheet 32. All errors within the HPU identified as an RSS value of ±0.2% full scale.

The POT input scaling within the HPU (reference SRS 2237400-1, sheet 19) is scaled for 5 Vdc (4095 counts) full scale.

The system accuracy was then obtained by the following

$$\text{System Accuracy RSS} = \sqrt{(15.01)^2 + (0.2)^2} = \pm 15.01\%$$

For comparison purposes, the requirement specified in 14 CFR Part 135, Appendix C is ±3%.

Note: The contribution of the HPU accuracy is 1.3% in reference to note 1 in 14 CFR Part 135, Appendix C.

Installed Accuracy: The Cyclic position sensor is rigged per procedure to be within ±3% of Travel.

A-13 CYCLIC POSITION (LATERAL) ACCURACY.

The performance specifications were obtained from the Bell Sensor drawing P/N 412-074-101 in order to identify the error contribution of the control motion transducer. The performance information for the HPU was obtained from the Teledyne System Requirements Specification. The accuracy analysis consisted of the following.

From Bell Specification 412-074-101, Rev E, dated 2/11/93:

- Accuracy — Review of the performance data in Note 2, Item A1, shows the resistance tolerance over the entire environmental range is ±15%. The linearity tolerance, indicated in A-2 is ±0.5% over the entire operating range.

The nonrigged sensor accuracy is then

$$\text{Sensor RSS accuracy (nonrigged)} = \sqrt{(15.01)^2 + (0.5)^2} = \pm 15.01\%$$

Note: The accuracy above does not include the mechanical misalignment due to mechanical tolerance in the sensor package.

The input of the HPU (reference channel #6 of SRS 2237400-1 page C-2) is identified as a POT-type input were the accuracy of that input type is specified in paragraph 3.2.1.2.3 of SRS 2237400-1, sheet 32. All errors within the HPU identified as an RSS value of ±0.2% full scale.

The POT input scaling within the HPU (reference SRS 2237400-1, sheet 19) is scaled for 5 Vdc (4095 counts) full scale.

The system accuracy was then obtained by the following

$$\text{System Accuracy RSS} = \sqrt{(15.01)^2 + (0.2)^2} = \pm 15.01\%$$

For comparison purposes, the requirement specified in 14 CFR Part 135, Appendix C is ±3%.

Note: The contribution of the HPU accuracy is 1.3% in reference to note 1 in 14 CFR Part 135, Appendix C.

Installed Accuracy: The Cyclic position sensor is rigged per procedure to be within ±3% of Travel.

A-14 PEDAL POSITION ACCURACY.

The performance specifications were obtained from the Bell Sensor drawing P/N 412-074-101 in order to identify the error contribution of the control motion transducer. The performance information for the HPU was obtained from the Teledyne System Requirements Specification. The accuracy analysis consisted of the following.

From Bell Specification 412-074-101, Rev E, dated 2/11/93:

Accuracy — Review of the performance data in Note 2, Item A1, shows the resistance tolerance over the entire environmental range is ±15%. The linearity tolerance, indicated in A-2 is ±0.5% over the entire operating range.

The nonrigged sensor accuracy is then:

$$\text{Sensor RSS accuracy (nonrigged)} = \sqrt{(15.01)^2 + (0.5)^2} = \pm 15.01\%$$

Note: The accuracy above does not include the mechanical misalignment due to mechanical tolerance in the sensor package.

The input of the HPU (reference channel #6 of SRS 2237400-1 page C-2) is identified as a POT-type input where the accuracy of that input type is specified in paragraph 3.2.1.2.3 of SRS 2237400-1, sheet 32. All errors within the HPU identified as an RSS value of ±0.2% full scale.

The POT input scaling within the HPU (reference SRS 2237400-1, sheet 19) is scaled for 5 Vdc (4095 counts) full scale.

The system accuracy was then obtained by the following

$$\text{System Accuracy RSS} = \sqrt{(15.01)^2 + (0.2)^2} = \pm 15.01\%$$

For comparison purposes, the requirement specified in 14 CFR Part 135, Appendix C is ±3%.

Note: The contribution of the HPU accuracy is 1.3% in reference to note 1 in 14 CFR Part 135, Appendix C.

Installed Accuracy: The Pedal position sensor is rigged per procedure to be within ±3% of Travel.

A-15 TIME AND DATE ACCURACY.

Time is provided by a time clock circuit internal to the Teledyne HPU. Subsequently the time accuracy is solely associated to the internal HPU circuit. The accuracy of the time circuit was provided by Teledyne and is as follows

Installed system accuracy = ±0.125% per hour or ±4.5 sec

For comparison, the requirement specified in 14 CFR Part 135, Appendix C is ±0.125% per hour.

Note: The time signal is not derived from an existing aircraft signal source, and subsequently, the requirement in note 1 of 14 CFR Part 135, Appendix C does not apply.

Time/Date Setup: Note the time and date are set by the operator using a HPU front panel function.

A-16 GROSS WEIGHT.

Gross weight is a pilot-entered value. It is set to the nearest 50 pounds.

A-17 ON GROUND DISCRETE.

Validates each flight leg. Accuracy is not applicable.

A-18 AIRCRAFT FLIGHT HOURS.

Cumulative aircraft flight hours are operator entered and tracked by the HUMS system for system integrity checking. Usage data is not used if the current value does not match the aircraft's logbook.

APPENDIX B—ERROR ANALYSIS OF V_h FOR THE BELL HELICOPTER MODEL 412

OAT (°C)	Palt	GWT	1/sqr(sig)	DenAlt	V_h	dV_h	% Error	nstart	nend
								3	308
-55	0	8000	0.870103	-9821.29	129.6284		0.104057		
-50	0	8000	0.880018	-8997.33	129.4333		0.109118		
-45	0	8000	0.889822	-8195.86	129.2224		0.113382		
-40	0	8000	0.899519	-7415.79	128.997		0.116892		
-35	0	8000	0.909112	-6656.11	128.7584		0.119728		
-30	0	8000	0.918606	-5915.88	128.5078		0.121944		
-25	0	8000	0.928002	-5194.21	128.2462		0.123573		
-20	0	8000	0.937304	-4490.28	127.9748		0.12467		
-15	0	8000	0.946515	-3803.31	127.6943		0.125284		
-10	0	8000	0.955637	-3132.58	127.4056		0.125436		
-5	0	8000	0.964673	-2477.41	127.1094		0.125182		
0	0	8000	0.973625	-1837.15	126.8065		0.124531		
5	0	8000	0.982495	-1211.2	126.4974		0.12352		
10	0	8000	0.991286	-598.998	126.1827		0.123478		
15	0	8000	1	0	125.863		0.129877		
20	0	8000	1.008638	586.2985	125.5387		0.136235		
25	0	8000	1.017204	1160.374	125.2103		0.142558		
-55	0	10000	0.870103	-9821.29	130.248		0.201197		
-50	0	10000	0.880018	-8997.33	129.7735		0.203273		
-45	0	10000	0.889822	-8195.86	129.3054		0.205106		
-40	0	10000	0.899519	-7415.79	128.8436		0.206717		
-35	0	10000	0.909112	-6656.11	128.3881		0.208116		
-30	0	10000	0.918606	-5915.88	127.9387		0.209325		
-25	0	10000	0.928002	-5194.21	127.4952		0.210346		
-20	0	10000	0.937304	-4490.28	127.0577		0.211202		
-15	0	10000	0.946515	-3803.31	126.6259		0.211892		
-10	0	10000	0.955637	-3132.58	126.1998		0.212439		
-5	0	10000	0.964673	-2477.41	125.7792		0.212858		
0	0	10000	0.973625	-1837.15	125.364		0.213137		
5	0	10000	0.982495	-1211.2	124.9542		0.213298		
10	0	10000	0.991286	-598.998	124.5495		0.213348		
15	0	10000	1	0	124.15		0.213285		
20	0	10000	1.008638	586.2985	123.7555		0.21312		
25	0	10000	1.017204	1160.374	123.3658		0.21286		
-55	0	11900	0.870103	-9821.29	125.4123		0.224303		
-50	0	11900	0.880018	-8997.33	125.4101		0.177622		
-45	0	11900	0.889822	-8195.86	125.3439		0.174769		
-40	0	11900	0.899519	-7415.79	125.2187		0.174122		
-35	0	11900	0.909112	-6656.11	125.0392		0.175543		
-30	0	11900	0.918606	-5915.88	124.8096		0.178916		
-25	0	11900	0.928002	-5194.21	124.5339		0.184134		

ERROR ANALYSIS OF V_h FOR THE BELL HELICOPTER MODEL 412 (Continued)

OAT (°C)	Palt	GWT	1/sqr(sig)	DenAlt	V_h	dV_h	% Error	nstart	nend
-20	0	11900	0.937304	-4490.28	124.2155		0.19127		
-15	0	11900	0.946515	-3803.31	123.8578		0.201549		
-10	0	11900	0.955637	-3132.58	123.4637		0.21342		
-5	0	11900	0.964673	-2477.41	123.036		0.2268		
0	0	11900	0.973625	-1837.15	122.5771		0.24164		
5	0	11900	0.982495	-1211.2	122.0896		0.257872		
10	0	11900	0.991286	-598.998	121.5754		0.275448		
15	0	11900	1	0	121.0366		0.294336		
20	0	11900	1.008638	586.2985	120.475		0.314472		
25	0	11900	1.017204	1160.374	119.8923		0.335836		
-55	3000	8000	0.919125	-5875.72	128.4937		0.131695		
-50	3000	8000	0.929598	-5072.71	128.2005		0.133877		
-45	3000	8000	0.939955	-4291.62	127.8953		0.13536		
-40	3000	8000	0.950198	-3531.39	127.579		0.136221		
-35	3000	8000	0.960332	-2791.03	127.2529		0.136511		
-30	3000	8000	0.970361	-2069.62	126.918		0.136264		
-25	3000	8000	0.980286	-1366.3	126.5751		0.135536		
-20	3000	8000	0.990113	-680.267	126.2252		0.134975		
-15	3000	8000	0.999842	-10.7626	125.8688		0.142364		
-10	3000	8000	1.009478	642.9112	125.5068		0.14968		
-5	3000	8000	1.019023	1281.426	125.1397		0.156947		
0	3000	8000	1.028479	1905.406	124.7681		0.164147		
5	3000	8000	1.03785	2515.437	124.3926		0.171304		
10	3000	8000	1.047136	3112.074	124.0136		0.17841		
15	3000	8000	1.05634	3695.84	123.6315		0.18549		
20	3000	8000	1.065466	4267.229	123.2467		0.192532		
25	3000	8000	1.074513	4826.709	122.8597		0.199553		
-55	3000	10000	0.919125	-5875.72	127.9141		0.226083		
-50	3000	10000	0.929598	-5072.71	127.4201		0.227014		
-45	3000	10000	0.939955	-4291.62	126.9333		0.227752		
-40	3000	10000	0.950198	-3531.39	126.4537		0.228296		
-35	3000	10000	0.960332	-2791.03	125.981		0.228668		
-30	3000	10000	0.970361	-2069.62	125.5152		0.228872		
-25	3000	10000	0.980286	-1366.3	125.0561		0.228932		
-20	3000	10000	0.990113	-680.267	124.6035		0.228845		
-15	3000	10000	0.999842	-10.7626	124.1572		0.228629		
-10	3000	10000	1.009478	642.9112	123.7172		0.228295		
-5	3000	10000	1.019023	1281.426	123.2832		0.227842		
0	3000	10000	1.028479	1905.406	122.8552		0.227282		
5	3000	10000	1.03785	2515.437	122.433		0.226627		
10	3000	10000	1.047136	3112.074	122.0165		0.225868		
15	3000	10000	1.05634	3695.84	121.6055		0.225032		

ERROR ANALYSIS OF V_h FOR THE BELL HELICOPTER MODEL 412 (Continued)

OAT (°C)	Palt	GWT	1/sqr(sig)	DenAlt	V_h	dV_h	% Error	nstart	nend
20	3000	10000	1.065466	4267.229	121.1999		0.22411		
25	3000	10000	1.074513	4826.709	120.7996		0.22311		
-55	3000	11900	0.919125	-5875.72	124.7956		0.188724		
-50	3000	11900	0.929598	-5072.71	124.4824		0.196596		
-45	3000	11900	0.939955	-4291.62	124.1169		0.208037		
-40	3000	11900	0.950198	-3531.39	123.7034		0.221857		
-35	3000	11900	0.960332	-2791.03	123.246		0.237488		
-30	3000	11900	0.970361	-2069.62	122.7484		0.254859		
-25	3000	11900	0.980286	-1366.3	122.214		0.273903		
-20	3000	11900	0.990113	-680.267	121.6458		0.294549		
-15	3000	11900	0.999842	-10.7626	121.0465		0.316744		
-10	3000	11900	1.009478	642.9112	120.4189		0.34043		
-5	3000	11900	1.019023	1281.426	119.7653		0.365578		
0	3000	11900	1.028479	1905.406	119.0877		0.392125		
5	3000	11900	1.03785	2515.437	118.3882		0.420052		
10	3000	11900	1.047136	3112.074	117.6686		0.449321		
15	3000	11900	1.05634	3695.84	116.9307		0.479899		
20	3000	11900	1.065466	4267.229	116.1759		0.511768		
25	3000	11900	1.074513	4826.709	115.4056		0.544893		
-55	6000	8000	0.972043	-1949.64	126.8607		0.149267		
-50	6000	8000	0.983119	-1167.48	126.4753		0.14889		
-45	6000	8000	0.994072	-406.669	126.0813		0.152169		
-40	6000	8000	1.004905	333.827	125.6797		0.160692		
-35	6000	8000	1.015623	1054.966	125.2714		0.169103		
-30	6000	8000	1.026229	1757.648	124.8573		0.17743		
-25	6000	8000	1.036726	2442.708	124.438		0.185661		
-20	6000	8000	1.047118	3110.93	124.0143		0.193826		
-15	6000	8000	1.057408	3763.049	123.5868		0.201923		
-10	6000	8000	1.067599	4399.754	123.156		0.20997		
-5	6000	8000	1.077693	5021.693	122.7224		0.217961		
0	6000	8000	1.087694	5629.473	122.2865		0.225912		
5	6000	8000	1.097603	6223.666	121.8488		0.233831		
10	6000	8000	1.107424	6804.813	121.4094		0.241715		
15	6000	8000	1.117159	7373.423	120.9689		0.24957		
20	6000	8000	1.126809	7929.977	120.5276		0.257403		
25	6000	8000	1.136378	8474.932	120.0856		0.265225		
-55	6000	10000	0.972043	-1949.64	125.4373		0.246854		
-50	6000	10000	0.983119	-1167.48	124.9254		0.246674		
-45	6000	10000	0.994072	-406.669	124.4216		0.246318		
-40	6000	10000	1.004905	333.827	123.9258		0.24582		
-35	6000	10000	1.015623	1054.966	123.4376		0.245173		
-30	6000	10000	1.026229	1757.648	122.9569		0.244394		

ERROR ANALYSIS OF V_h FOR THE BELL HELICOPTER MODEL 412 (Continued)

OAT (°C)	Palt	GWT	1/sqr(sig)	DenAlt	V_h	dV_h	% Error	nstart	nend
-25	6000	10000	1.036726	2442.708	122.4836		0.243488		
-20	6000	10000	1.047118	3110.93	122.0173		0.242474		
-15	6000	10000	1.057408	3763.049	121.558		0.241351		
-10	6000	10000	1.067599	4399.754	121.1054		0.240136		
-5	6000	10000	1.077693	5021.693	120.6594		0.238823		
0	6000	10000	1.087694	5629.473	120.2198		0.237424		
5	6000	10000	1.097603	6223.666	119.7865		0.235952		
10	6000	10000	1.107424	6804.813	119.3592		0.2344		
15	6000	10000	1.117159	7373.423	118.938		0.232786		
20	6000	10000	1.126809	7929.977	118.5225		0.231098		
25	6000	10000	1.136378	8474.932	118.1127		0.229348		
-55	6000	11900	0.972043	-1949.64	122.6607		0.27971		
-50	6000	11900	0.983119	-1167.48	122.0541		0.303172		
-45	6000	11900	0.994072	-406.669	121.4062		0.328493		
-40	6000	11900	1.004905	333.827	120.7209		0.355625		
-35	6000	11900	1.015623	1054.966	120.0017		0.384497		
-30	6000	11900	1.026229	1757.648	119.2516		0.415059		
-25	6000	11900	1.036726	2442.708	118.4735		0.447273		
-20	6000	11900	1.047118	3110.93	117.6701		0.481105		
-15	6000	11900	1.057408	3763.049	116.8436		0.516503		
-10	6000	11900	1.067599	4399.754	115.9962		0.553452		
-5	6000	11900	1.077693	5021.693	115.13		0.591923		
0	6000	11900	1.087694	5629.473	114.2467		0.631893		
5	6000	11900	1.097603	6223.666	113.3479		0.673344		
10	6000	11900	1.107424	6804.813	112.4353		0.716259		
15	6000	11900	1.117159	7373.423	111.5102		0.760625		
20	6000	11900	1.126809	7929.977	110.5739		0.806437		
25	6000	11900	1.136378	8474.932	109.6275		0.853693		
-55	9000	8000	1.029261	1956.627	124.7371		0.196996		
-50	9000	8000	1.040989	2718.044	124.2652		0.206475		
-45	9000	8000	1.052587	3458.681	123.7881		0.215844		
-40	9000	8000	1.064058	4179.538	123.3065		0.225102		
-35	9000	8000	1.075406	4881.555	122.8212		0.234284		
-30	9000	8000	1.086636	5565.6	122.3329		0.243389		
-25	9000	8000	1.097751	6232.492	121.8422		0.252428		
-20	9000	8000	1.108755	6882.994	121.3495		0.261406		
-15	9000	8000	1.119651	7517.82	120.8554		0.270341		
-10	9000	8000	1.130442	8137.641	120.3603		0.279237		
-5	9000	8000	1.14113	8743.085	119.8646		0.288093		
0	9000	8000	1.151719	9334.747	119.3686		0.296921		
5	9000	8000	1.162212	9913.184	118.8727		0.305727		
10	9000	8000	1.172611	10478.92	118.3772		0.314883		

ERROR ANALYSIS OF V_h FOR THE BELL HELICOPTER MODEL 412 (Continued)

OAT (°C)	Palt	GWT	1/sqr(sig)	DenAlt	V_h	dV_h	% Error	nstart	nend
15	9000	8000	1.182919	11032.45	117.8822		0.324547		
20	9000	8000	1.193138	11574.25	117.388		0.33422		
25	9000	8000	1.203269	12104.75	116.8948		0.343912		
-55	9000	10000	1.029261	1956.627	122.8199		0.26342		
-50	9000	10000	1.040989	2718.044	122.292		0.26213		
-45	9000	10000	1.052587	3458.681	121.7729		0.260704		
-40	9000	10000	1.064058	4179.538	121.2624		0.259159		
-35	9000	10000	1.075406	4881.555	120.7602		0.257495		
-30	9000	10000	1.086636	5565.6	120.2662		0.255736		
-25	9000	10000	1.097751	6232.492	119.78		0.253882		
-20	9000	10000	1.108755	6882.994	119.3015		0.251933		
-15	9000	10000	1.119651	7517.82	118.8305		0.249908		
-10	9000	10000	1.130442	8137.641	118.3667		0.247806		
-5	9000	10000	1.14113	8743.085	117.9099		0.245634		
0	9000	10000	1.151719	9334.747	117.46		0.243399		
5	9000	10000	1.162212	9913.184	117.0168		0.2411		
10	9000	10000	1.172611	10478.92	116.5801		0.238751		
15	9000	10000	1.182919	11032.45	116.1497		0.236351		
20	9000	10000	1.193138	11574.25	115.7254		0.233901		
25	9000	10000	1.203269	12104.75	115.3072		0.231408		
-55	9000	11900	1.029261	1956.627	119.0304		0.458179		
-50	9000	11900	1.040989	2718.044	118.1478		0.496498		
-45	9000	11900	1.052587	3458.681	117.2345		0.536725		
-40	9000	11900	1.064058	4179.538	116.2938		0.578822		
-35	9000	11900	1.075406	4881.555	115.3285		0.622763		
-30	9000	11900	1.086636	5565.6	114.3412		0.668529		
-25	9000	11900	1.097751	6232.492	113.3343		0.716098		
-20	9000	11900	1.108755	6882.994	112.31		0.765446		
-15	9000	11900	1.119651	7517.82	111.2702		0.816571		
-10	9000	11900	1.130442	8137.641	110.2167		0.86946		
-5	9000	11900	1.14113	8743.085	109.1511		0.924115		
0	9000	11900	1.151719	9334.747	108.0749		0.98053		
5	9000	11900	1.162212	9913.184	106.9895		1.038712		
10	9000	11900	1.172611	10478.92	105.896		1.098674		
15	9000	11900	1.182919	11032.45	104.7956		1.160408		
20	9000	11900	1.193138	11574.25	103.6893		1.223934		
25	9000	11900	1.203269	12104.75	102.5781		1.289279		
-55	12000	8000	1.091235	5842.753	122.1307		0.268161		
-50	12000	8000	1.10367	6583.535	121.578		0.278479		
-45	12000	8000	1.115965	7304.099	121.0232		0.28872		
-40	12000	8000	1.128127	8005.419	120.467		0.298882		
-35	12000	8000	1.140159	8688.409	119.9099		0.308981		

ERROR ANALYSIS OF V_h FOR THE BELL HELICOPTER MODEL 412 (Continued)

OAT (°C)	Palt	GWT	1/sqr(sig)	DenAlt	V_h	dV_h	% Error	nstart	nend
-30	12000	8000	1.152065	9353.918	119.3524		0.319015		
-25	12000	8000	1.163849	10002.74	118.795		0.329015		
-20	12000	8000	1.175516	10635.61	118.2381		0.338979		
-15	12000	8000	1.187067	11253.23	117.6819		0.349716		
-10	12000	8000	1.198508	11856.25	117.127		0.360668		
-5	12000	8000	1.20984	12445.29	116.5734		0.371628		
0	12000	8000	1.221067	13020.91	116.0216		0.382596		
5	12000	8000	1.232192	13583.67	115.4716		0.393575		
10	12000	8000	1.243217	14134.08	114.9237		0.404573		
15	12000	8000	1.254145	14672.61	114.3781		0.415588		
20	12000	8000	1.264979	15199.72	113.8349		0.426626		
25	12000	8000	1.275721	15715.84	113.2942		0.437679		
-55	12000	10000	1.091235	5842.753	120.0647		0.275641		
-50	12000	10000	1.10367	6583.535	119.5223		0.273241		
-45	12000	10000	1.115965	7304.099	118.9895		0.270739		
-40	12000	10000	1.128127	8005.419	118.4659		0.268155		
-35	12000	10000	1.140159	8688.409	117.9513		0.265483		
-30	12000	10000	1.152065	9353.918	117.4454		0.262736		
-25	12000	10000	1.163849	10002.74	116.9479		0.259919		
-20	12000	10000	1.175516	10635.61	116.4586		0.257042		
-15	12000	10000	1.187067	11253.23	115.9772		0.254102		
-10	12000	10000	1.198508	11856.25	115.5035		0.251115		
-5	12000	10000	1.20984	12445.29	115.0372		0.248074		
0	12000	10000	1.221067	13020.91	114.5783		0.244993		
5	12000	10000	1.232192	13583.67	114.1264		0.241871		
10	12000	10000	1.243217	14134.08	113.6813		0.238704		
15	12000	10000	1.254145	14672.61	113.2429		0.235512		
20	12000	10000	1.264979	15199.72	112.811		0.232282		
25	12000	10000	1.275721	15715.84	112.3854		0.229027		
-55	12000	11900	1.091235	5842.753	113.9281		0.735382		
-50	12000	11900	1.10367	6583.535	112.7867		0.791251		
-45	12000	11900	1.115965	7304.099	111.6247		0.849307		
-40	12000	11900	1.128127	8005.419	110.4446		0.909514		
-35	12000	11900	1.140159	8688.409	109.2488		0.971894		
-30	12000	11900	1.152065	9353.918	108.0395		1.036449		
-25	12000	11900	1.163849	10002.74	106.8185		1.103185		
-20	12000	11900	1.175516	10635.61	105.5876		1.172131		
-15	12000	11900	1.187067	11253.23	104.3483		1.243286		
-10	12000	11900	1.198508	11856.25	103.1021		1.316677		
-5	12000	11900	1.20984	12445.29	101.8502		1.392345		
0	12000	11900	1.221067	13020.91	100.5938		1.470304		
5	12000	11900	1.232192	13583.67	99.33396		1.550603		

ERROR ANALYSIS OF V_h FOR THE BELL HELICOPTER MODEL 412 (Continued)

OAT (°C)	Palt	GWT	1/sqr(sig)	DenAlt	V_h	dV_h	% Error	nstart	nend
10	12000	11900	1.243217	14134.08	98.07162		1.633272		
15	12000	11900	1.254145	14672.61	96.80765		1.718346		
20	12000	11900	1.264979	15199.72	95.54282		1.805895		
25	12000	11900	1.275721	15715.84	94.27785		1.895957		
-55	15000	8000	1.158481	9708.388	119.0496		0.349537		
-50	15000	8000	1.171682	10428.64	118.4216		0.3609		
-45	15000	8000	1.184735	11129.24	117.7946		0.372193		
-40	15000	8000	1.197646	11811.13	117.1689		0.384293		
-35	15000	8000	1.210419	12475.19	116.545		0.396719		
-30	15000	8000	1.223059	13122.26	115.9233		0.409147		
-25	15000	8000	1.23557	13753.1	115.304		0.421581		
-20	15000	8000	1.247955	14368.44	114.6874		0.434025		
-15	15000	8000	1.260219	14968.94	114.0738		0.446479		
-10	15000	8000	1.272364	15555.26	113.4634		0.458947		
-5	15000	8000	1.284395	16127.97	112.8562		0.471448		
0	15000	8000	1.296313	16687.65	112.2526		0.483954		
5	15000	8000	1.308124	17234.81	111.6526		0.496504		
10	15000	8000	1.319828	17769.97	111.0563		0.509069		
15	15000	8000	1.33143	18293.57	110.4638		0.521662		
20	15000	8000	1.342931	18806.08	109.8753		0.534289		
25	15000	8000	1.354335	19307.9	109.2907		0.546955		
-55	15000	10000	1.158481	9708.388	117.1741		0.283327		
-50	15000	10000	1.171682	10428.64	116.619		0.279814		
-45	15000	10000	1.184735	11129.24	116.0741		0.276238		
-40	15000	10000	1.197646	11811.13	115.539		0.272598		
-35	15000	10000	1.210419	12475.19	115.0135		0.268901		
-30	15000	10000	1.223059	13122.26	114.4971		0.265163		
-25	15000	10000	1.23557	13753.1	113.9897		0.261384		
-20	15000	10000	1.247955	14368.44	113.4909		0.257558		
-15	15000	10000	1.260219	14968.94	113.0005		0.253707		
-10	15000	10000	1.272364	15555.26	112.5182		0.249811		
-5	15000	10000	1.284395	16127.97	112.0437		0.245884		
0	15000	10000	1.296313	16687.65	111.5769		0.241942		
5	15000	10000	1.308124	17234.81	111.1175		0.237978		
10	15000	10000	1.319828	17769.97	110.6653		0.233979		
15	15000	10000	1.33143	18293.57	110.22		0.229982		
20	15000	10000	1.342931	18806.08	109.7816		0.22596		
25	15000	10000	1.354335	19307.9	109.3497		0.221926		
-55	15000	11900	1.158481	9708.388	107.3776		1.135184		
-50	15000	11900	1.171682	10428.64	105.9944		1.213346		
-45	15000	11900	1.184735	11129.24	104.6001		1.294261		
-40	15000	11900	1.197646	11811.13	103.1966		1.377965		

ERROR ANALYSIS OF V_h FOR THE BELL HELICOPTER MODEL 412 (Continued)

OAT (°C)	Palt	GWT	1/sqr(sig)	DenAlt	V_h	dV_h	% Error	nstart	nend
-35	15000	11900	1.210419	12475.19	101.7857		1.46451		
-30	15000	11900	1.223059	13122.26	100.3692		1.55394		
-25	15000	11900	1.23557	13753.1	98.94855		1.6463		
-20	15000	11900	1.247955	14368.44	97.52507		1.741683		
-15	15000	11900	1.260219	14968.94	96.09995		1.840138		
-10	15000	11900	1.272364	15555.26	94.67425		1.94173		
-5	15000	11900	1.284395	16127.97	93.24894		2.046542		
0	15000	11900	1.296313	16687.65	91.82489		2.154695		
5	15000	11900	1.308124	17234.81	90.40285		2.266247		
10	15000	11900	1.319828	17769.97	88.98351		2.381284		
15	15000	11900	1.33143	18293.57	87.56752		2.499972		
20	15000	11900	1.342931	18806.08	86.1554		2.622373		
25	15000	11900	1.354335	19307.9	84.74766		2.748657		